Equatorial Ionosphere: Dynamics, Scientific Results and Opportunities

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agenda

Magnetic Equator

Major regions of the ionosphere

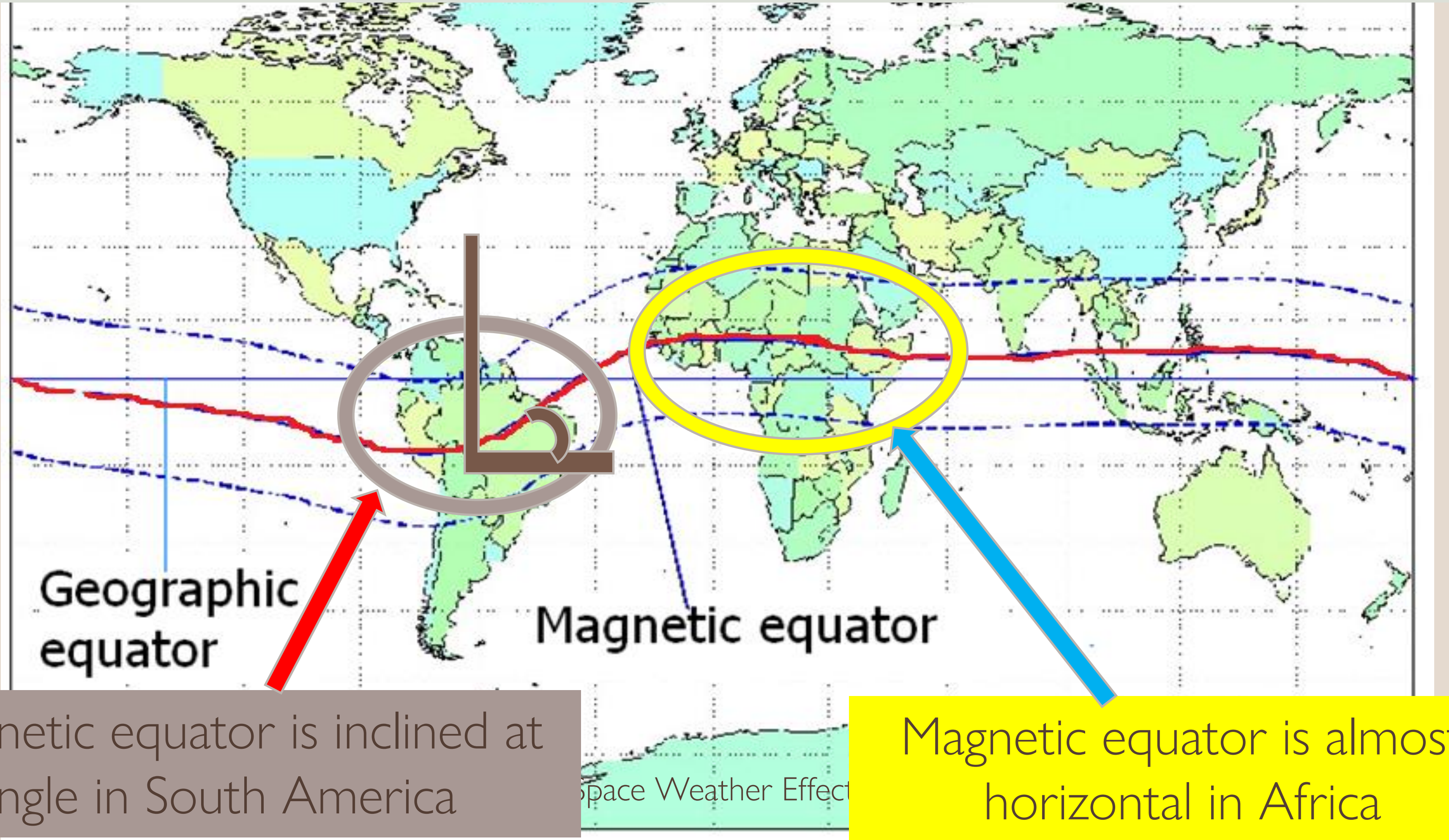
Equatorial Ionospheric phenomena

Transient variations of equatorial ionosphere

SUMMARY

Magnetic Equator

- Magnetic (dip) equator is defined as the locus of zero dip along the surface of the earth (Cohen, 1967)
- Its latitude varies along the geographical longitudes

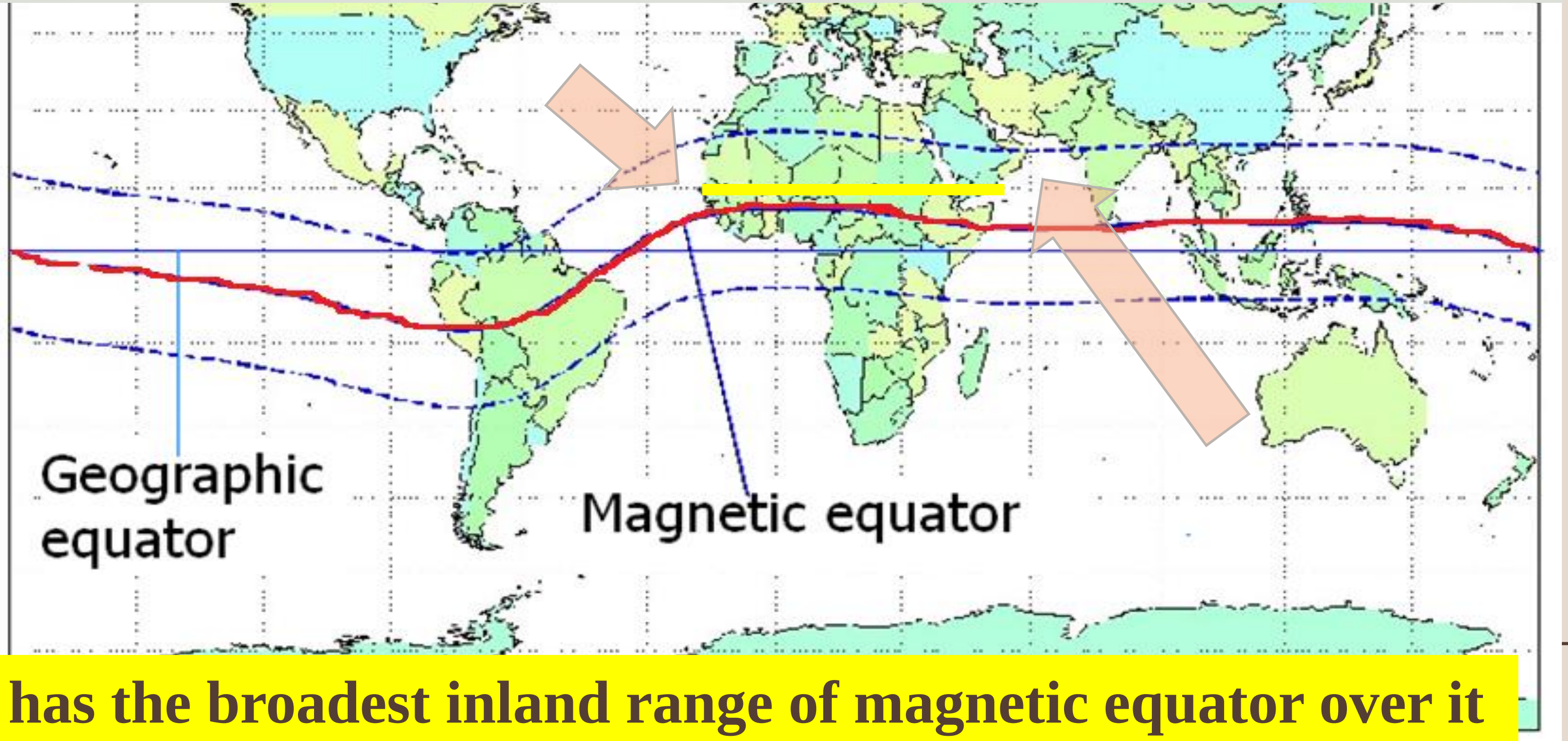


Magnetic equator is inclined at an angle in South America

Magnetic equator is almost horizontal in Africa

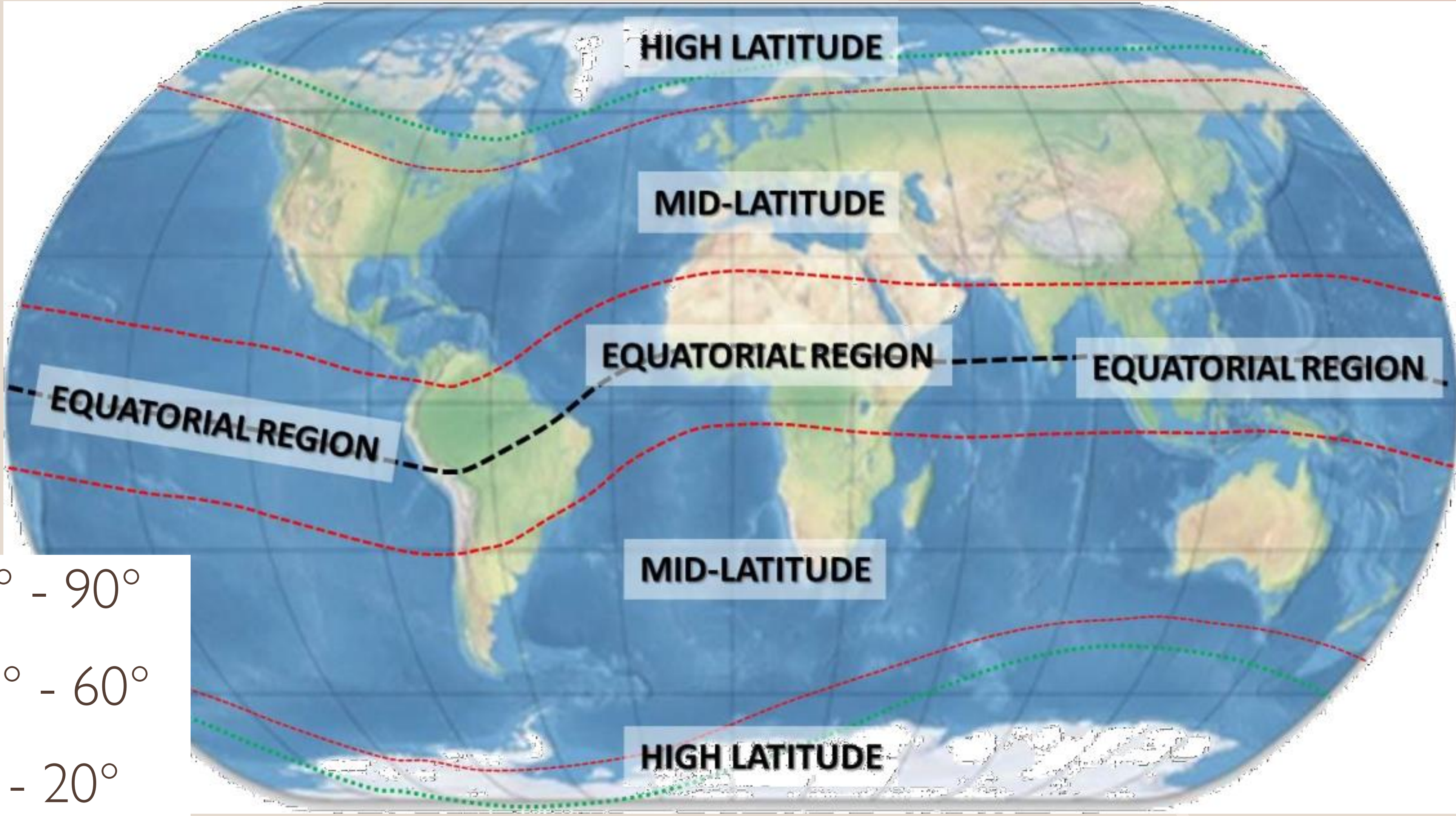
Magnetic Equator

- In the neighbourhood of magnetic equator, there is an unusual orientation of the magnetic field with relation to the Earth
- Charged particles move more readily along magnetic field lines
- Migration of charged particles along geomagnetic field lines is associated with a two-humped latitudinal distribution of electron density, with minimum at the magnetic equator



Africa has the broadest inland range of magnetic equator over it

3 major regions of the global ionosphere



- high-latitude ± 60° - 90°
- mid- latitude ± 20° - 60°
- equatorial ± 0 - 20°

Magnetic latitudes

Khamdan, 2018

Equatorial Ionosphere 1

- The ionosphere over the equatorial region/low latitudes possesses features that are distinct from those of other latitudes, because of:
    - the low inclination geomagnetic field lines and
    - the relatively larger fraction of the incident solar ionizing radiation that characterize this region
- characterized with the highest values of the peak-electron density with the most pronounced amplitude and phase scintillation effects
- At low latitudes where the magnetic field lines are quasi horizontal, the vertical transport of plasma is governed by zonal electric fields generated by ionospheric dynamo or by penetrating electric field originating from magnetospheric dynamo

Equatorial Ionosphere 2

- The upward propagating winds and waves, associated with tidal oscillation modes, gravity waves and planetary/Kelvin waves, interact with the magnetized conducting ionosphere of the dynamo region generating the electric fields

- The zonal component of the electric field produces vertical E × B plasma drift whose well-known manifestation is the equatorial plasma fountain that produces the equatorial ionization anomaly (EIA)

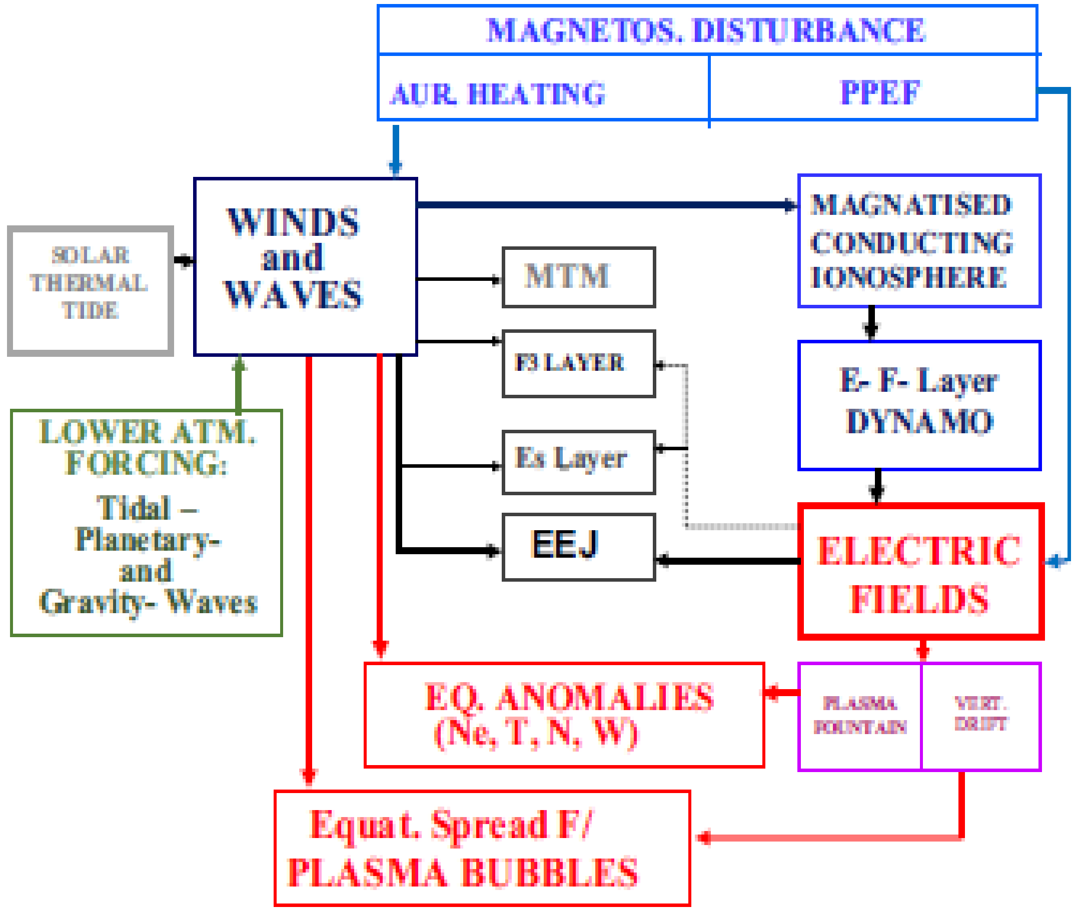


Fig. 1 A schematic showing the central role of the electric field in shaping the major low latitude ionospheric phenomena represented by *red colored boxes*. The "quiet time" electric fields are generated by *E*- and *F* layer dynamos operated by the winds and waves from lower atmosphere, in their upward propagation, interacting with the magnetized conducting ionosphere of the dynamo region. Perturbation electric field due to magnetospheric disturbance (*blue box*) is shown connecting to quiet time dynamo *E* field that varies also due to forcing form lower atmosphere

Abdu *Geosci. Lett. (2016) 3:11*

Equatorial Ionosphere 3

- The combined effect of the high radiation level from the sun, & the electric and the magnetic fields of the earth results in the electrons rising and moving along the horizontal lines of the magnetic field, forces ionization up into the F layer, concentrating at ± 20 ° from the magnetic equator this phenomenon is called the fountain effect (Abdu , *2016)*

- The electrons move as far as the geomagnetic latitudes of 10 to 20° causing the high concentration of electrons there which are often termed equatorial anomalies (Komjathy, 1997).

Equatorial Ionospheric Phenomena

- E layer – Equatorial electrojet

  - Counter Electrojet

- F layer – Equatorial Ionospheric anomaly,
  - Spread F
  - Plasma Bubbles
  - ionospheric Irregularities
  - ionospheric scintillations

Equatorial Ionospheric Anomaly EIA

- The F2 layer in the vicinity of the magnetic dip equator is characterized by a depression in the ionization density or "trough" at the equator and two humps, one on each side of the equator (at about ±*17 - 20*° *magnetic latitude) during the* day that lasts for several hours after sunset.

- This interesting phenomenon is called the "equatorial anomaly" or "Appleton anomaly" (Appleton, 1946). The cause of the anomaly is often attributed to the so-called "fountain effect"

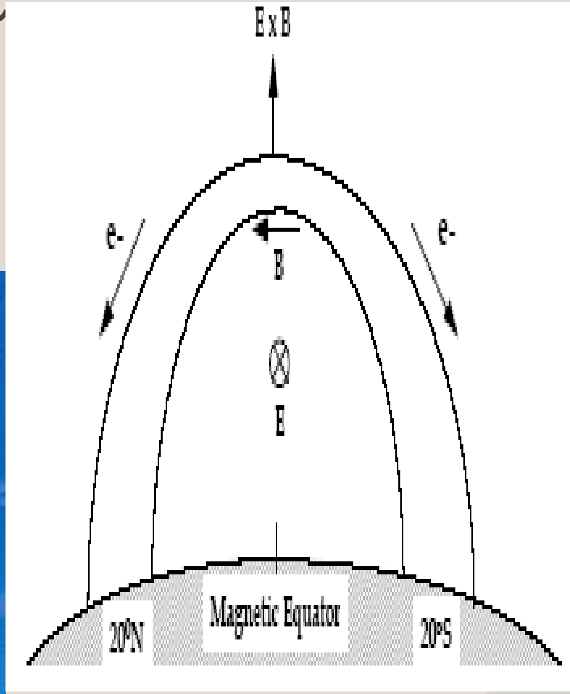
https://tenor.com/view/fountain-gif-7624014

Equatorial plasma fountain effect

- the eastward electric field at the equator that gives rise to an upward E×*B* drift during the daytime

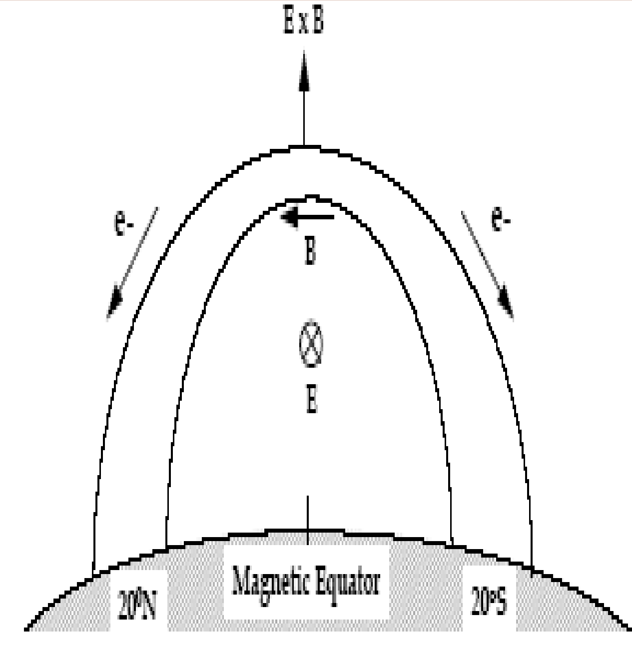
- After the plasma is lifted to greater heights it is able to diffuse downward along magnetic field lines under the influence of gravity and pressure gradient forces.

- The net result is the formation of a plasma “fountain” which produces an enhanced plasma concentration (crest) at higher latitudes and a reduced plasma concentration (trough) at the equator



Equatorial Plasma Fountain

- The daytime dynamo generated eastward electric field combined with the northward geomagnetic field lifts the equatorial ionosphere to 700 km to over one thousand kilometers.
- After losing momentum, the electrons diffuse along the field lines to either side of the equator to form two crests

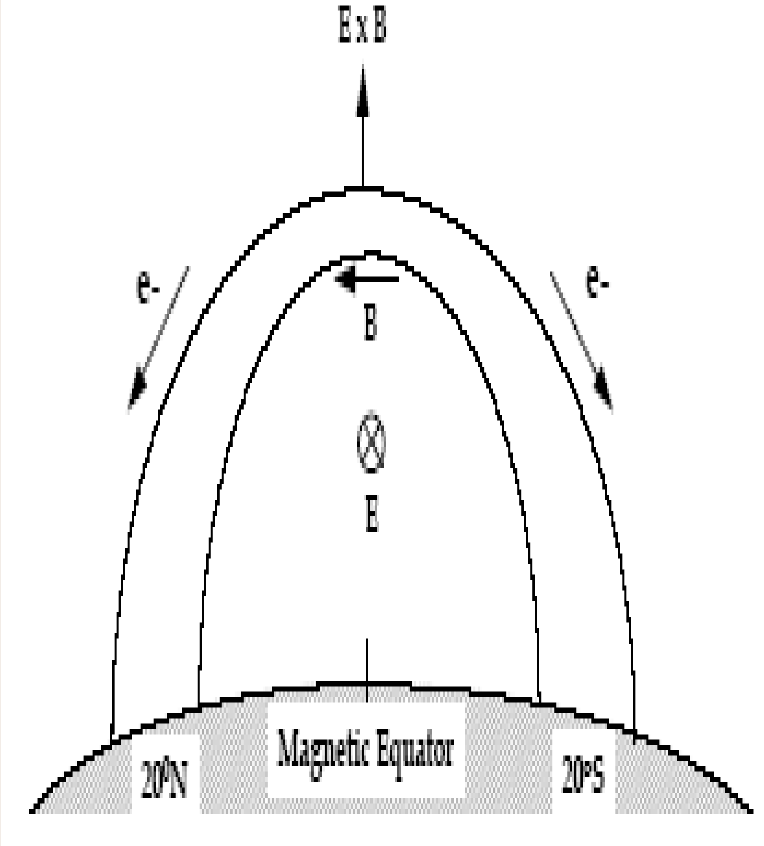


[Yeh et al 2001]

Equatorial Anomaly Crest

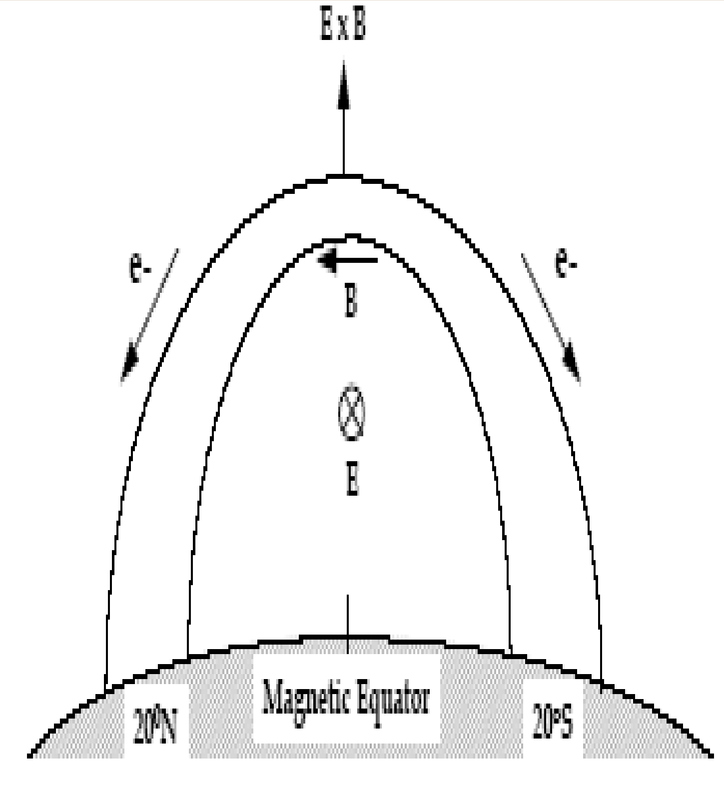
- In response to the diurnal variations of the dynamo electric field [Fejer, 1981], the anomaly crest begins to form around 09:00 LT on a normal day
- As time progresses, the anomaly crest intensifies and moves with a speed of about 1° per hour to a higher latitude

[Yeh et al 2001]



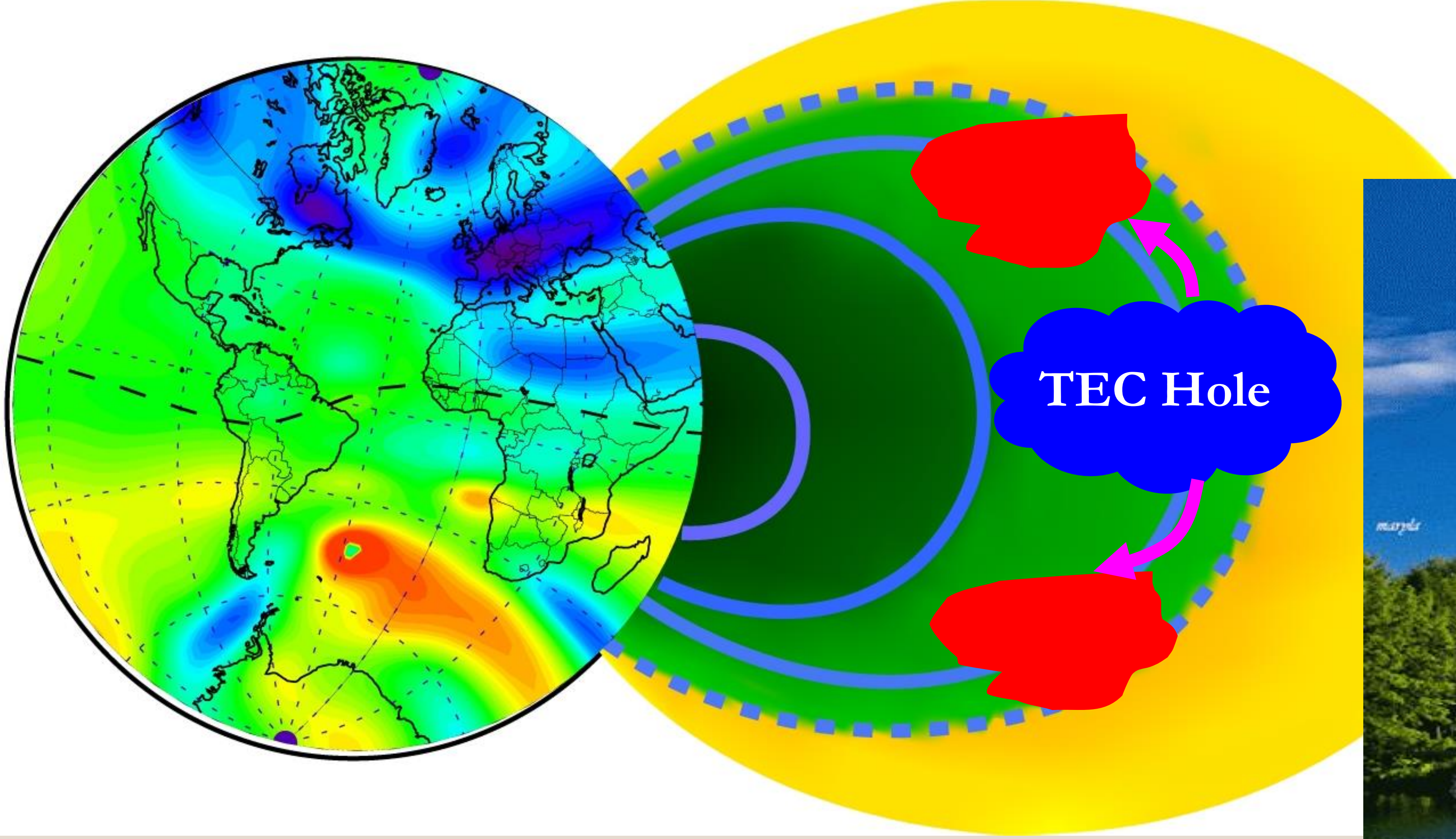
Equatorial Anomaly Crest

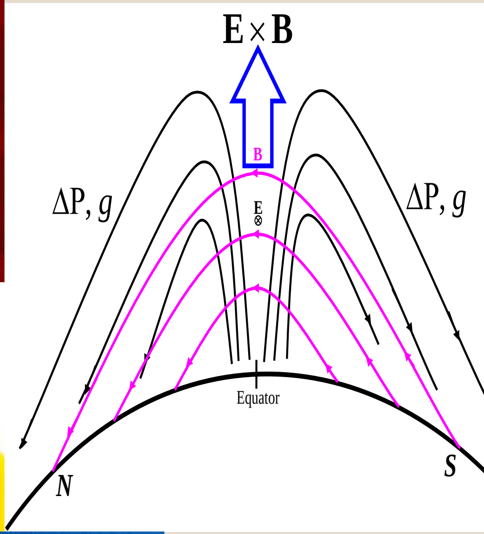
- This speed is maintained till shortly before noon when the poleward motion is slowed and reversed at around 14:00 LT
- During this time, the anomaly crest is most intense, showing the characteristic tilt, an approximate alignment of its core along the geomagnetic field lines and the asymmetric behavior
- Thereafter, the crest weakens and recedes slowly equatorward.
- On many days the crest is observed to linger into the night with a smaller spread in latitude



[Yeh et al 2001]

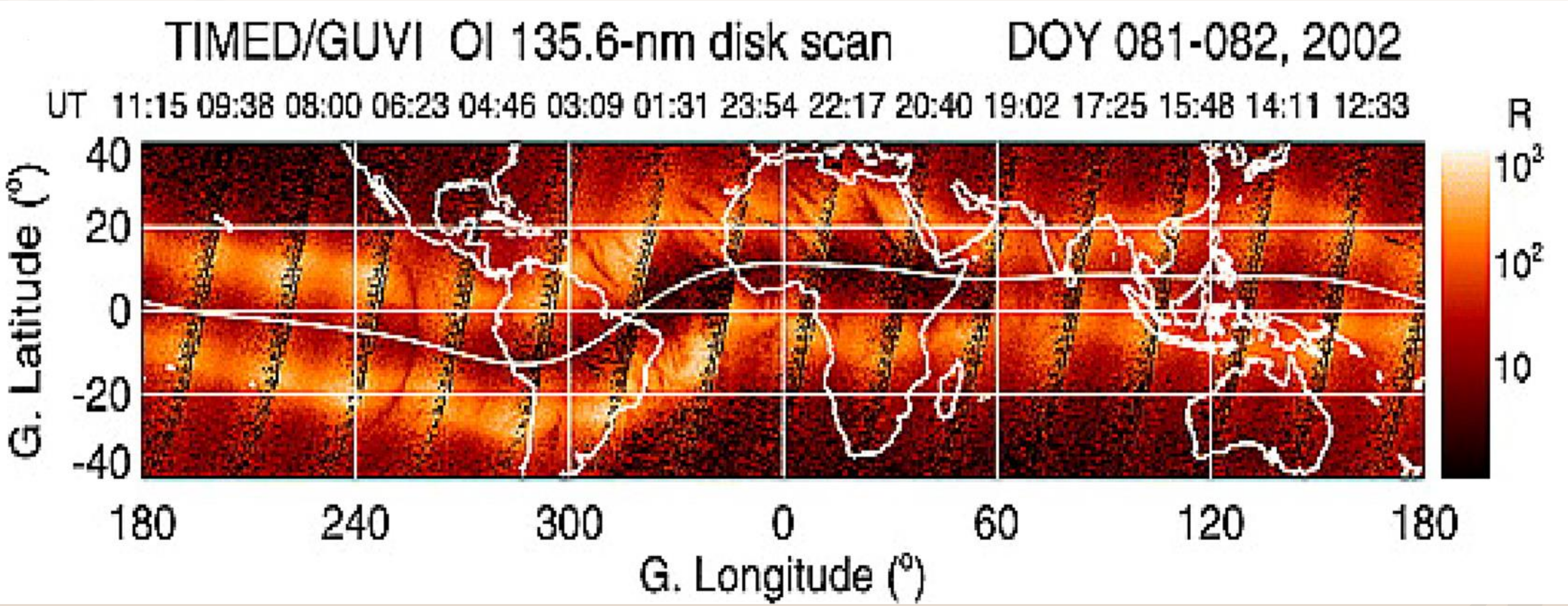
Equatorial Electrodynamics and the density structure





Courtesy: Endawoke Yizengaw , 2011.

EIA

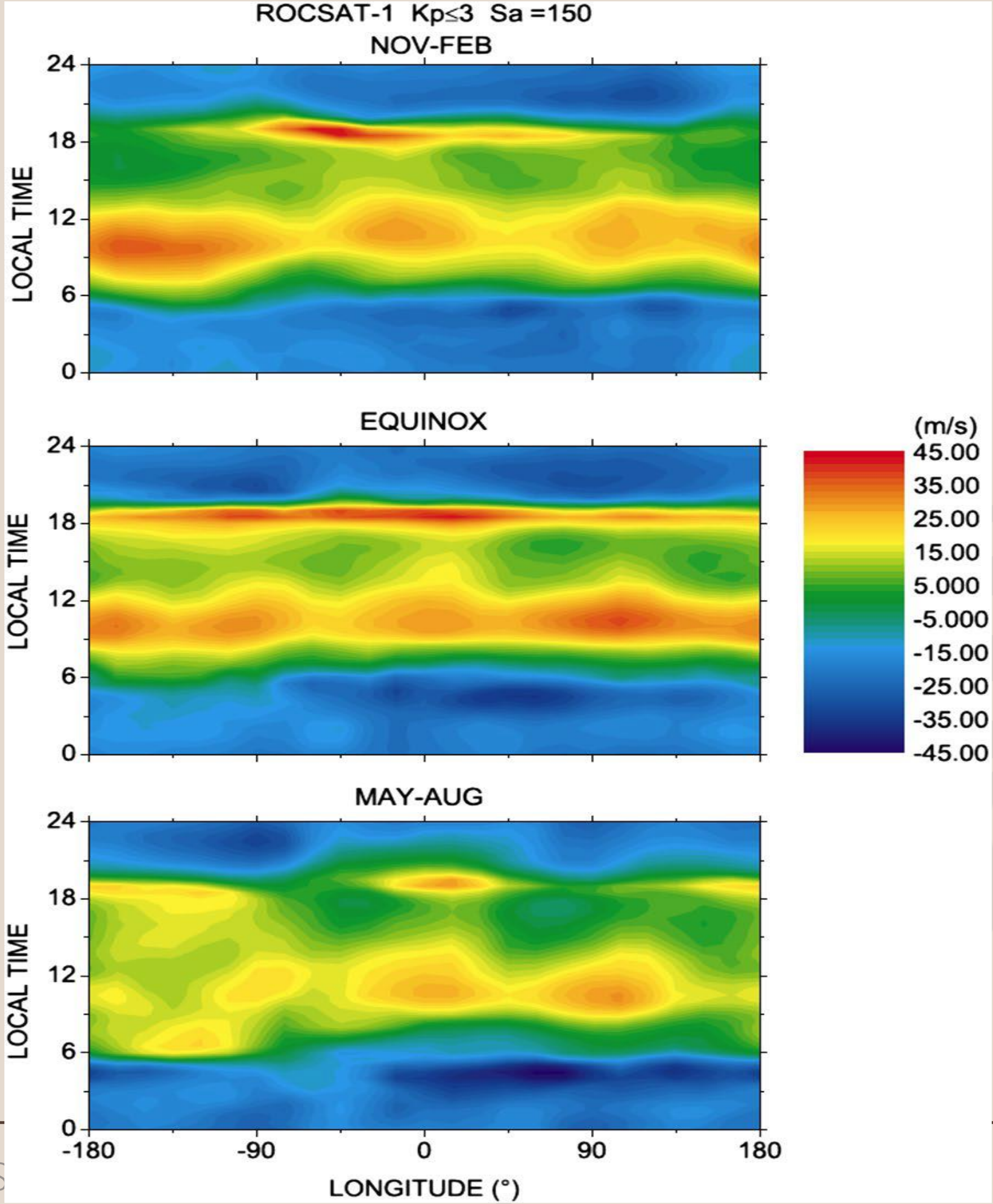


TIMED/GUVI 135.6 nm images extending in the entire longitude span showing the global distribution of the EIA brightness & the patches of brightness depletions indicating plasma bubbles symmetric on either side of the dip equator (Kil et al. 2006)

EIA

- The large plasma density of the EIA crests causes increased group delay of the GNSS signals leading to errors in positioning and navigation applications.

- The daytime upward plasma drift due to the E layer dynamo is responsible for the development of the EIA that attains maximum intensity in the afternoon hours



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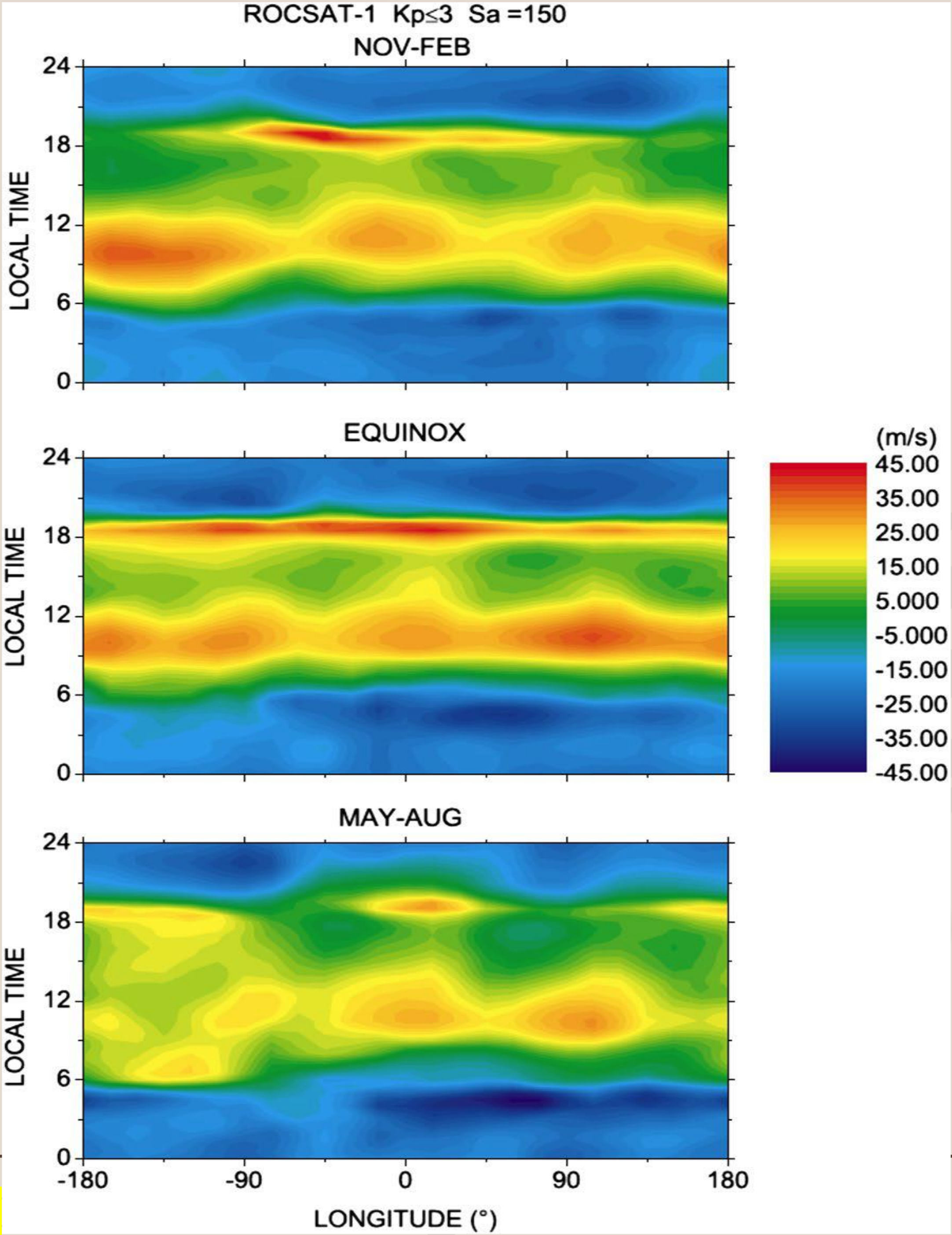
EIA

- An evening enhancement in the vertical drift (before its reversal to downward), known as the pre-reversal enhancement in the vertical drift (PRE), clearly observable around 18–19 LT during equinox and summer solstice at many longitudes
- The PRE vertical drift is responsible also for the structuring of the night-time ionosphere into plasma irregularities in wide spectrum of scale sizes that can cause severe scintillation (and loss of lock) of satellite signals



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Scintillations in Equatorial Region

- ✓Ionospheric scintillations are rapid and temporal fluctuations in the amplitude and phase of transionospheric radio signals resulting from electron density irregularities in the ionosphere

- ✓EIA -responsible for the formation of the plasma density irregularities that give rise to scintillations.

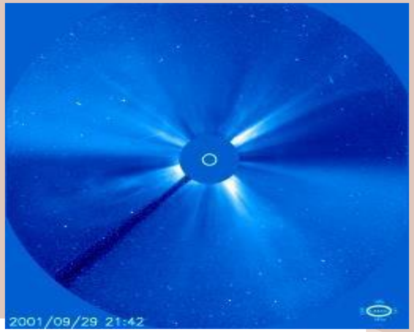
Equatorial Spread F ESF

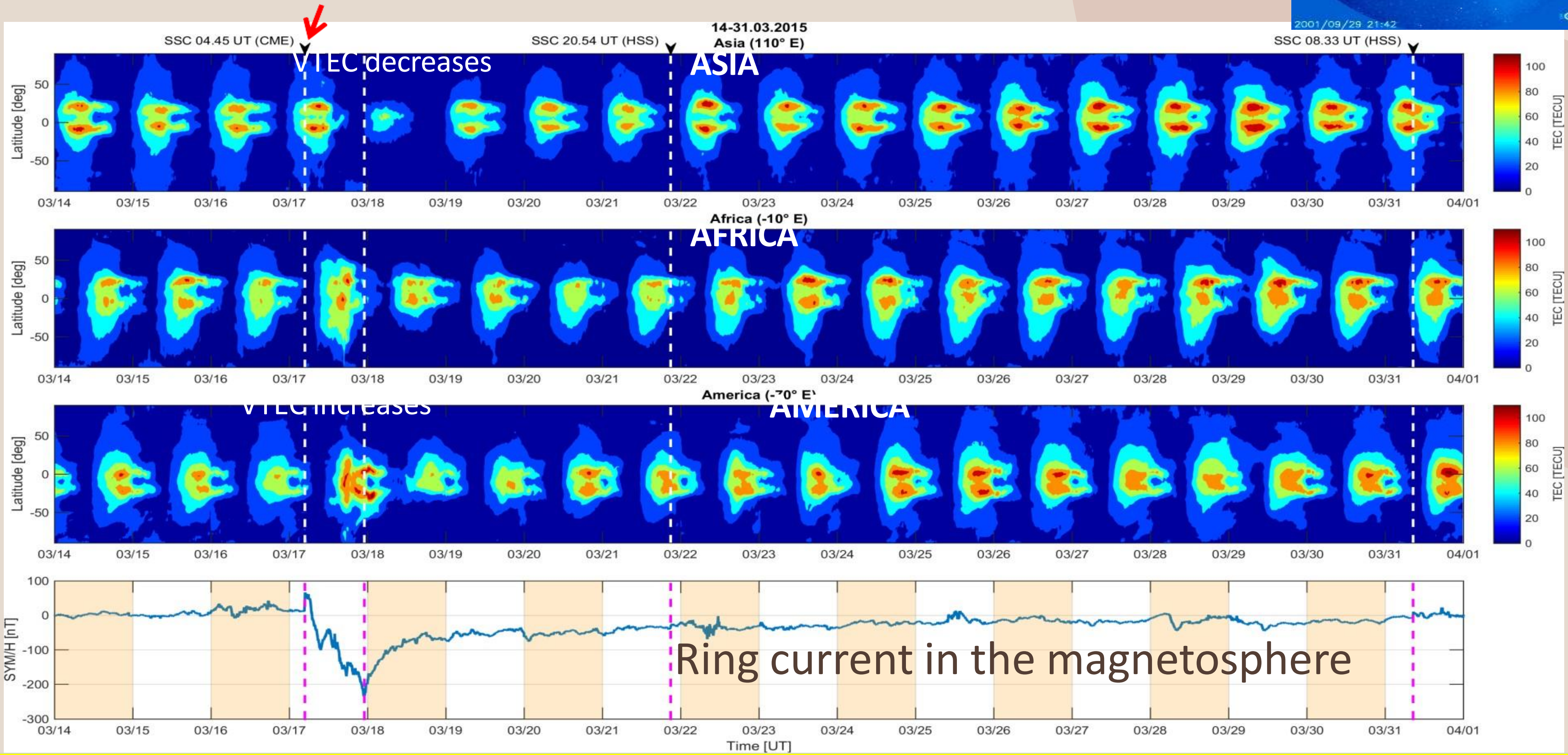
- ✓Irregularities in the equatorial F-region have been studied for decades
- ✓Abundant ionospheric density irregularities in equatorial ionosphere
- ✓These ionospheric irregularities are well known as equatorial spread-F (ESF) according to a nomenclature introduced after the appearance of spread echoes on ionograms.
- ✓The term 'spread-F irregularities' is synonymous with electron density fluctuations or structures on scales ranging from a few tens of centimeters to several hundred kilometers.

MAGNETIC STORM of St PATRICK's DAY : MAPS of VTEC

Variations near the magnetic Equator due to a CME (~200 GPS stations)

Impact of a CME (solar event, on March 15 ~ 04.45 - 02.00UT)





Courtesy

Christine Amory-Mazaudier (2022)

Nava,, et al., "Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

Equatorial Ionospheric Phenomena

- E layer – Equatorial electrojet
  - Counter Electrojet

Same effect, different Nomenclature

- Spread F - Ionosonde
- Plasma Bubbles - Optical Observation
- ionospheric irregularities - GNSS

- F layer – Equatorial Ionospheric anomaly,
  - Spread F
  - Plasma Bubbles
  - ionospheric Irregularities

Phenomena with similar drivers

EQUATORIAL PLASMA FOUNTAIN

EQUATORIAL IONOSPHERIC ANOMALY

EQUATORIAL PLASMA IRREGULARITIES

PLASMA BUBBLES

IONOSPHERIC SCINTILLATIONS

Sq & Equatorial Electrojet

- The E (dynamo) region of the equatorial ionosphere consists of 2 layers of currents responsible for the quiet solar daily variations in Earth's magnetic field:
  - *Worldwide solar quiet daily variation, WSq (altitude 118 $\pm$ 7 km), responsible for the global quiet daily variation observed in the earth's magnetic field.*
  - *Equatorial electrojet, EEJ - an intense current flowing eastward in the low latitude ionosphere within the narrow region flanking the dip equator (altitude 106 $\pm$ 2 km) (Chapman, 1951, Onwumechili, 1992)*
- Enhanced (Cowling) conductivity associated with the special equatorial magnetic field configuration results in the strong daytime EEJ currents

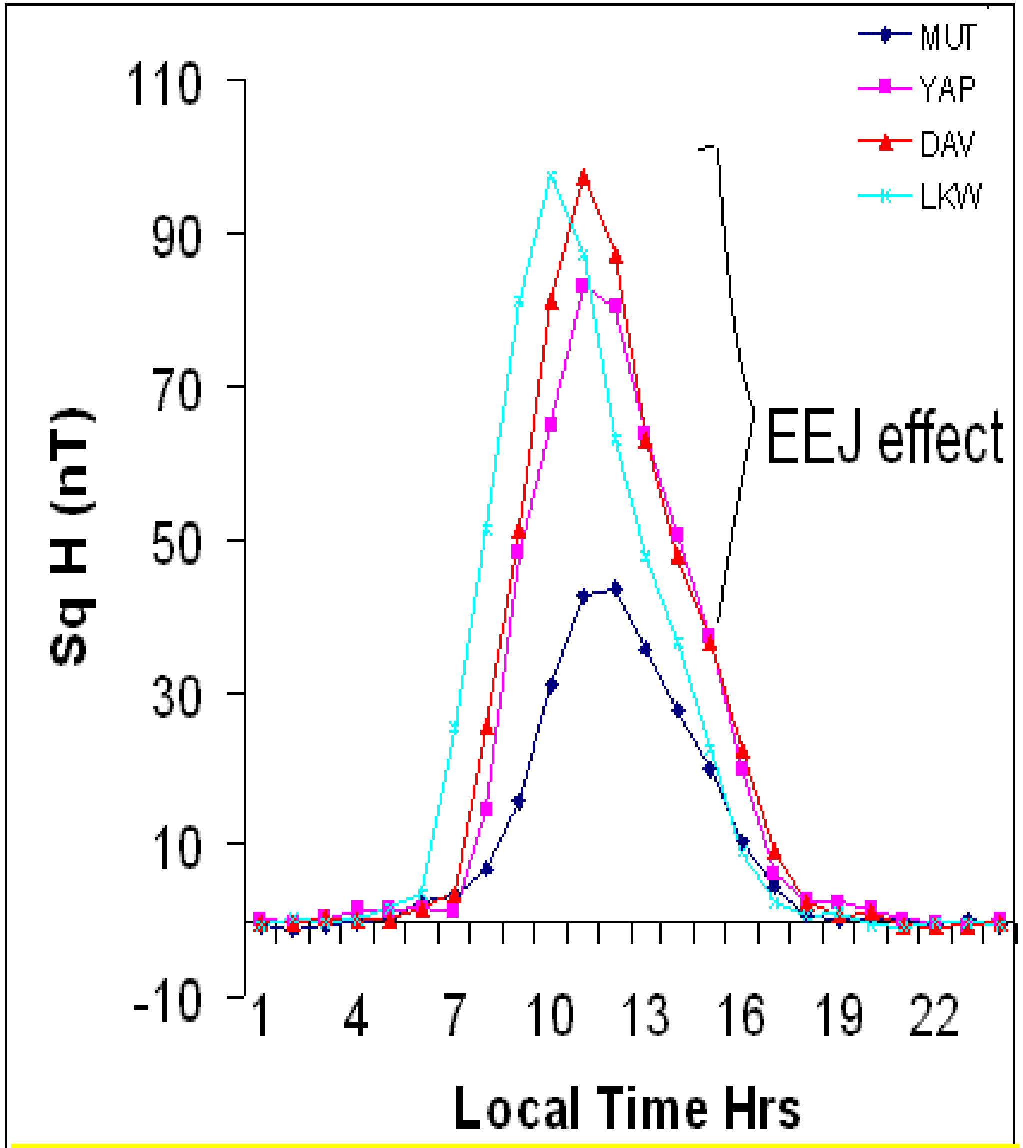
(Onwumechili, 1992a, 1992b, 1997; & Rabiu et al, 2013)

Sq & EEJ

- At the magnetic dip equator, where the geomagnetic field is horizontal, this electric field results in an enhanced eastward current flow within ± 3° of the magnetic equator, known as the equatorial electrojet

- This sudden enhancement, first observed at Huancayo in 1922, has been attributed to a narrow intense ionospheric current which flow eastwards within the narrow strip flanking the dip equator (Egedal, 1947, and others)

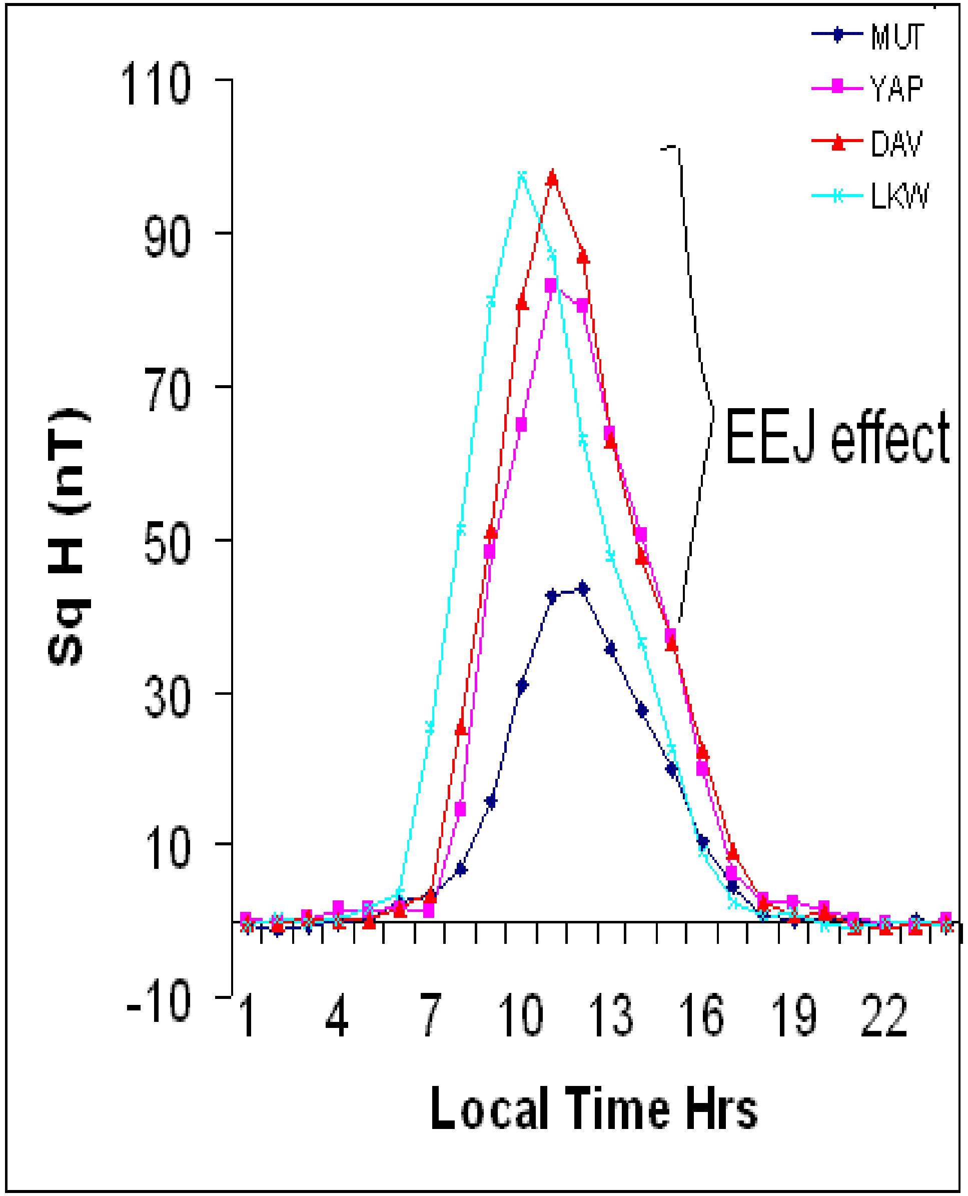
(Onwumechili, 1992a, 1992b, 1997; & Rabiu et al, 2013)



The enhancement of Sq at YAP, DAV and LAW on 8th April 2008 due to electrojet effect (After Rabiu et al, 2009a)

Sq & EEJ

This unique equatorial ionospheric current was later, in May 1951, named by Sydney Chapman 'the Equatorial electrojet' in his presidential address to the Physical Society of London.

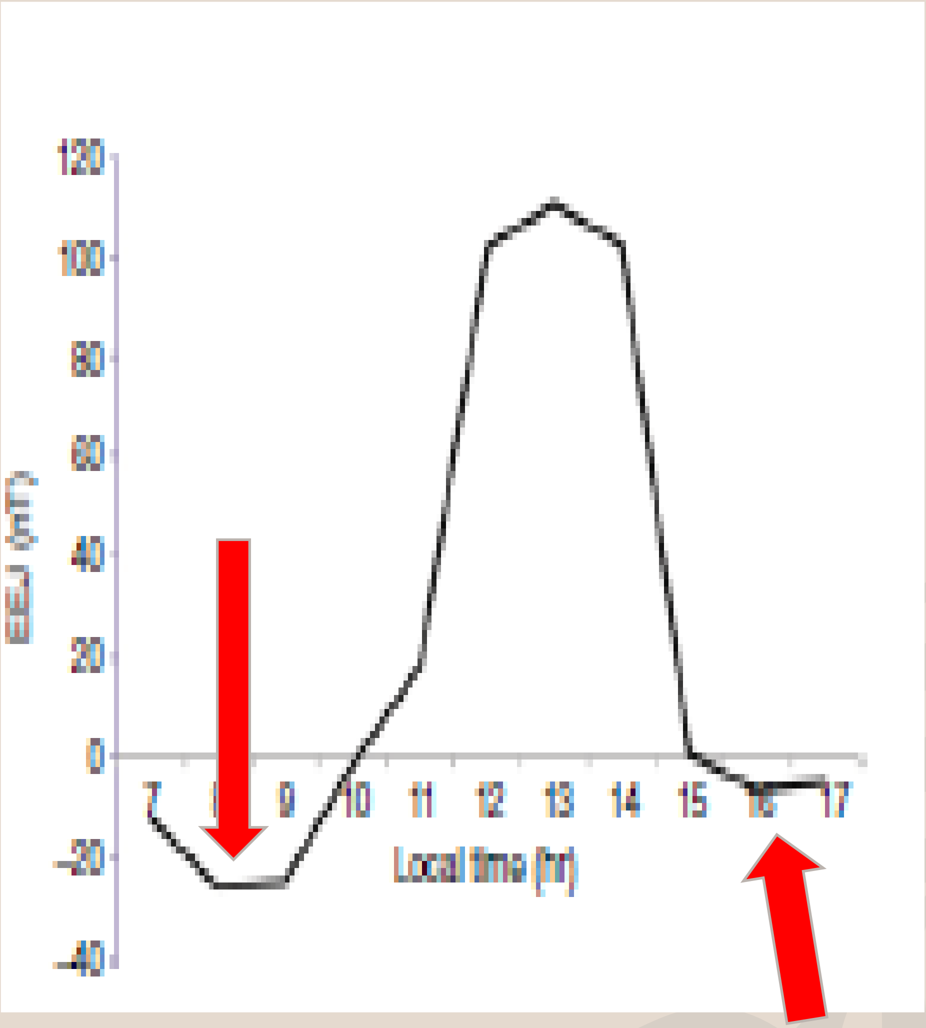


The enhancement of Sq at YAP, DAV and LKW on 8th April 2008 due to electrojet effect (After Rabiu et al, 2009a)

Counter electrojet CEJ

- On occasion, at quiet periods during certain hours of the day, particularly in the morning and evening hours,
- the EEJ reverses direction and flows westwards giving rise to the so-called 'counter electrojet (CEJ)' phenomenon

(Gouin, 1962; Gouin & Mayaud, 1967).

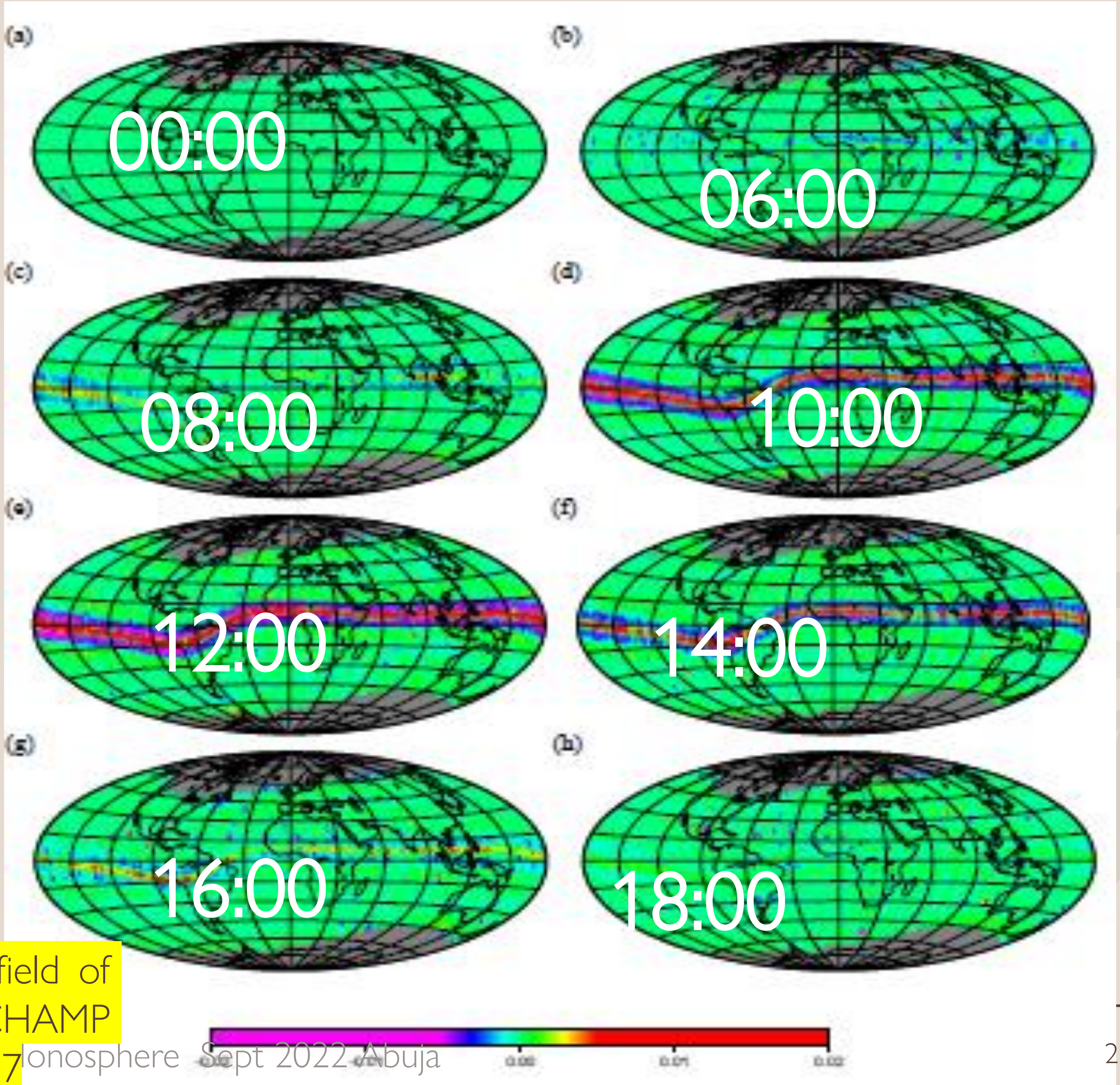


A typical diurnal variation of the equatorial electrojet (EEJ) on 2 March 2009 at Addis Ababa showing CEJ – morning and afternoon

Rabiu, et al., 2017

The field of the EEJ from CHAMP data

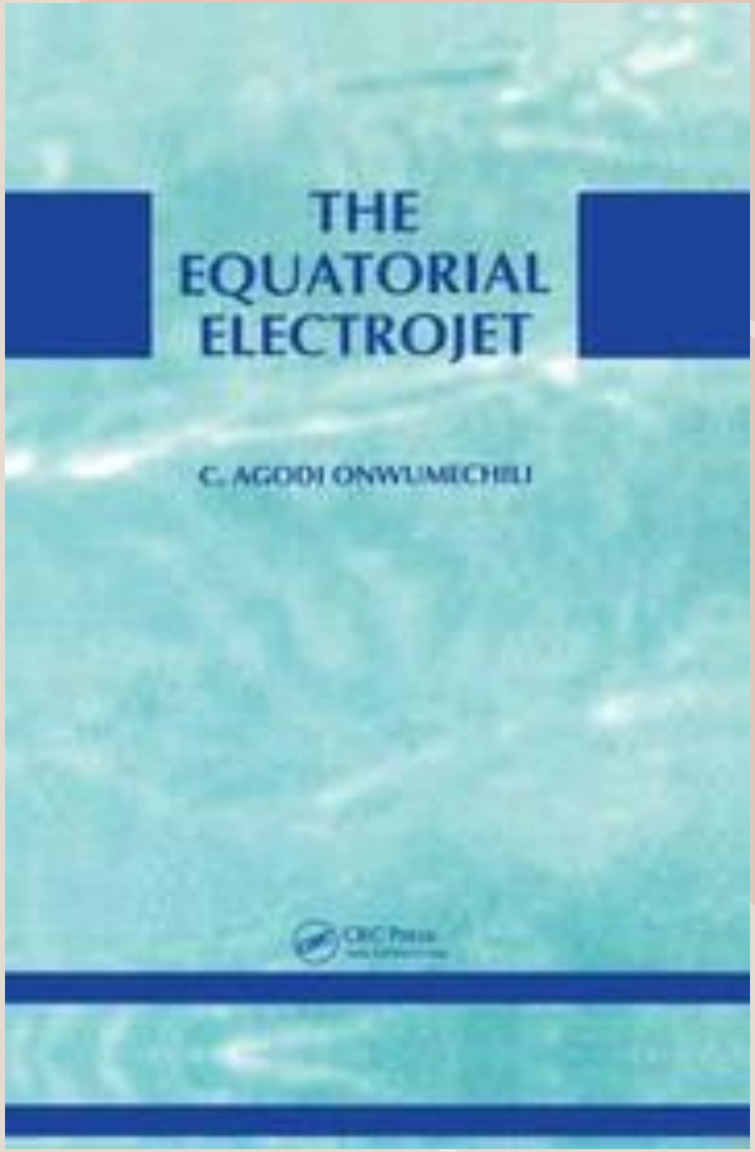
Variation with local time of the along-track second derivative of the equatorial electrojet field (in nT/s^2), longitudinal component



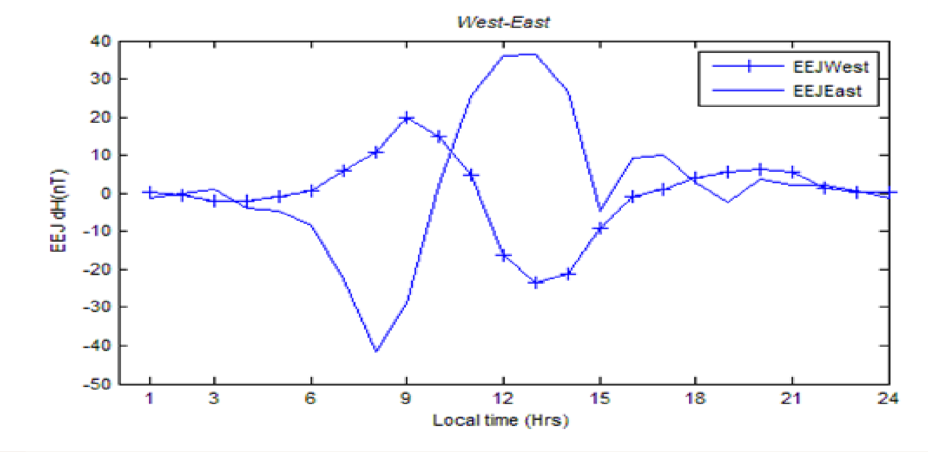
Le Mou¨el, et al., (2006). The field of the equatorial electrojet from CHAMP data, Ann. Geophys., 24, 515–527

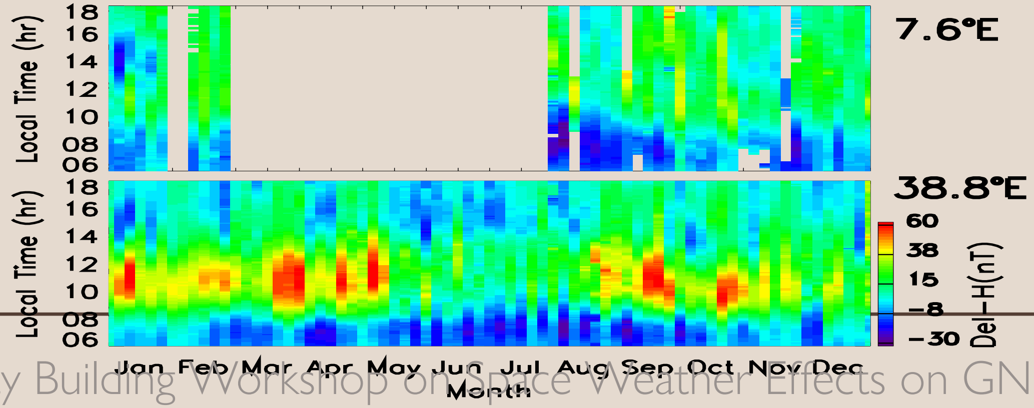
Manifestations of EEJ

- Spatial structures of its intense current density
- configurations & regular temporal variations of its current system
- magnetic fields of its current system
- the ionospheric plasma density irregularities generated by the turbulent flow of the EEJ current
- the electric fields and ionospheric plasma drifts in the dip equatorial zone
- the quiet counter equatorial electrojet CEJ
- temporal variabilities of the above phenomenon.



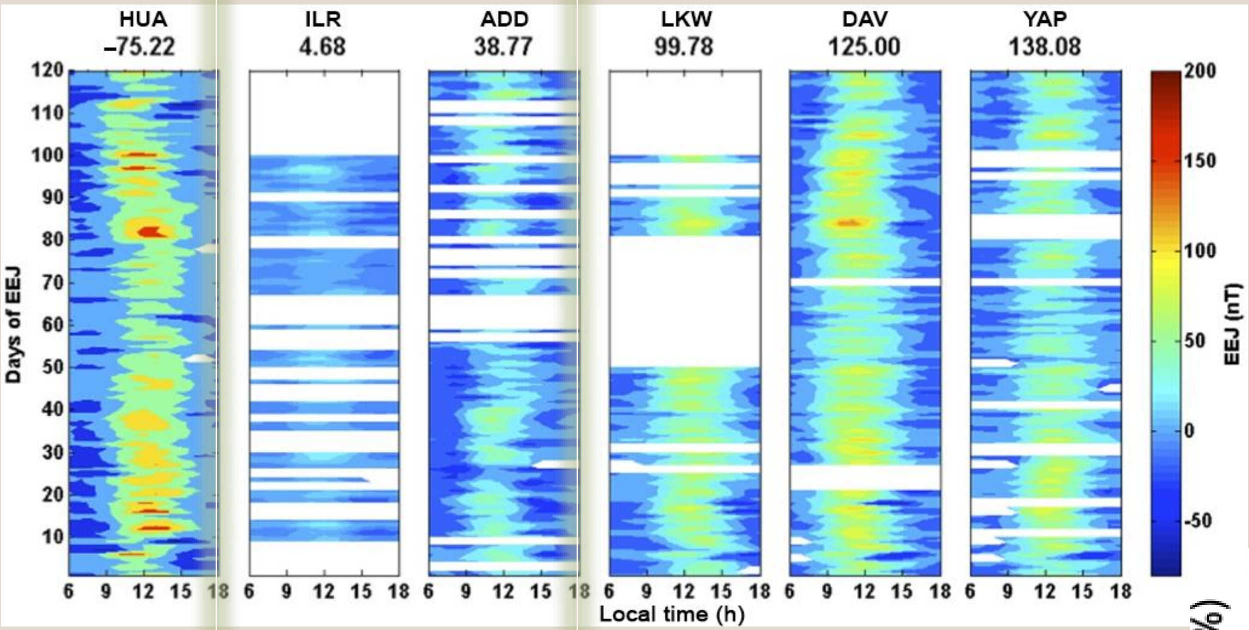
East-West Asymmetry in the African Equatorial Ionosphere





- Rabiu et al., (2011) for the first time clearly revealed that the western African EEJ appears weaker than eastern EEJ
- This discrepancy suggests that there is a process of re- injection of energy in the jet as it flows eastward
- This West-East Asymmetrical behavior in the EEJ strength in the African sector is further confirmed by Rabiu et al (2015) and Yizengaw et al., (2014) using data set from another set of array of magnetometers (AMBER).

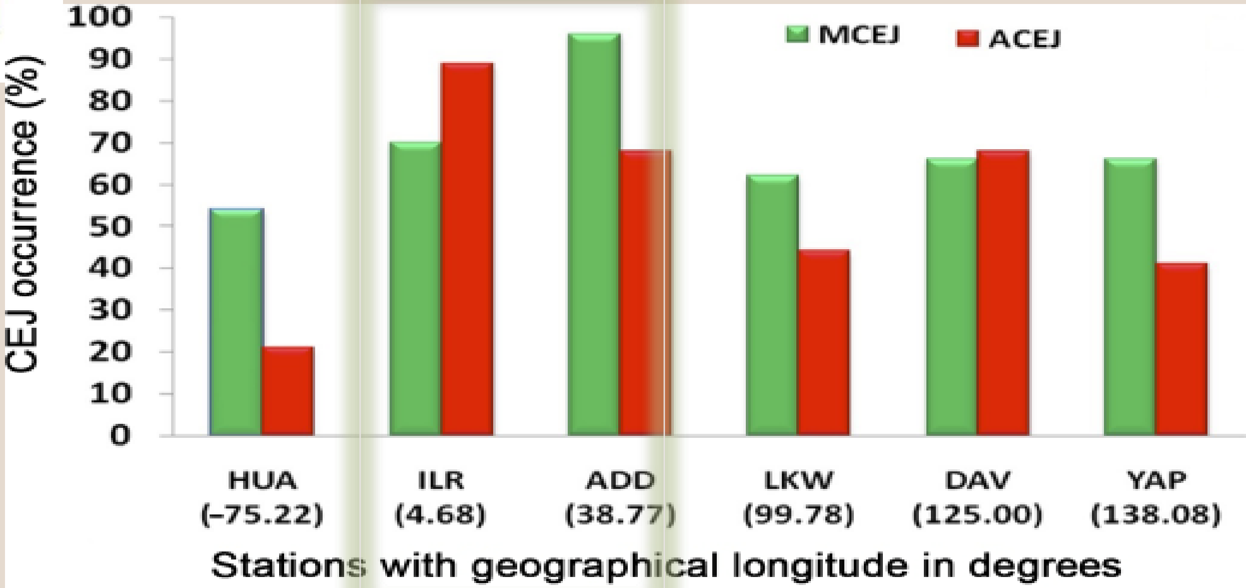
Longitudinal variation of EEJ



Variation of EEJ

- ✓ the African stations registered the greatest % of occurrence of the CEJ than elsewhere
- ✓ The greatest % occurrence of MCEJ was found at Addis Ababa (eastern Africa)
- ✓ the greatest % occurrence of afternoon CEJ was found at Ilorin (western Africa).

activities that support strong EEJ do inhibit occurrence of the CEJ.



Rabiu et al, 2016, 2017

Yearly % of occurrence of CEJ

LONGITUDINAL VARIABILITY OF EEJ

Comparison of EEJ at 210 MM with Indian & Brazil sectors

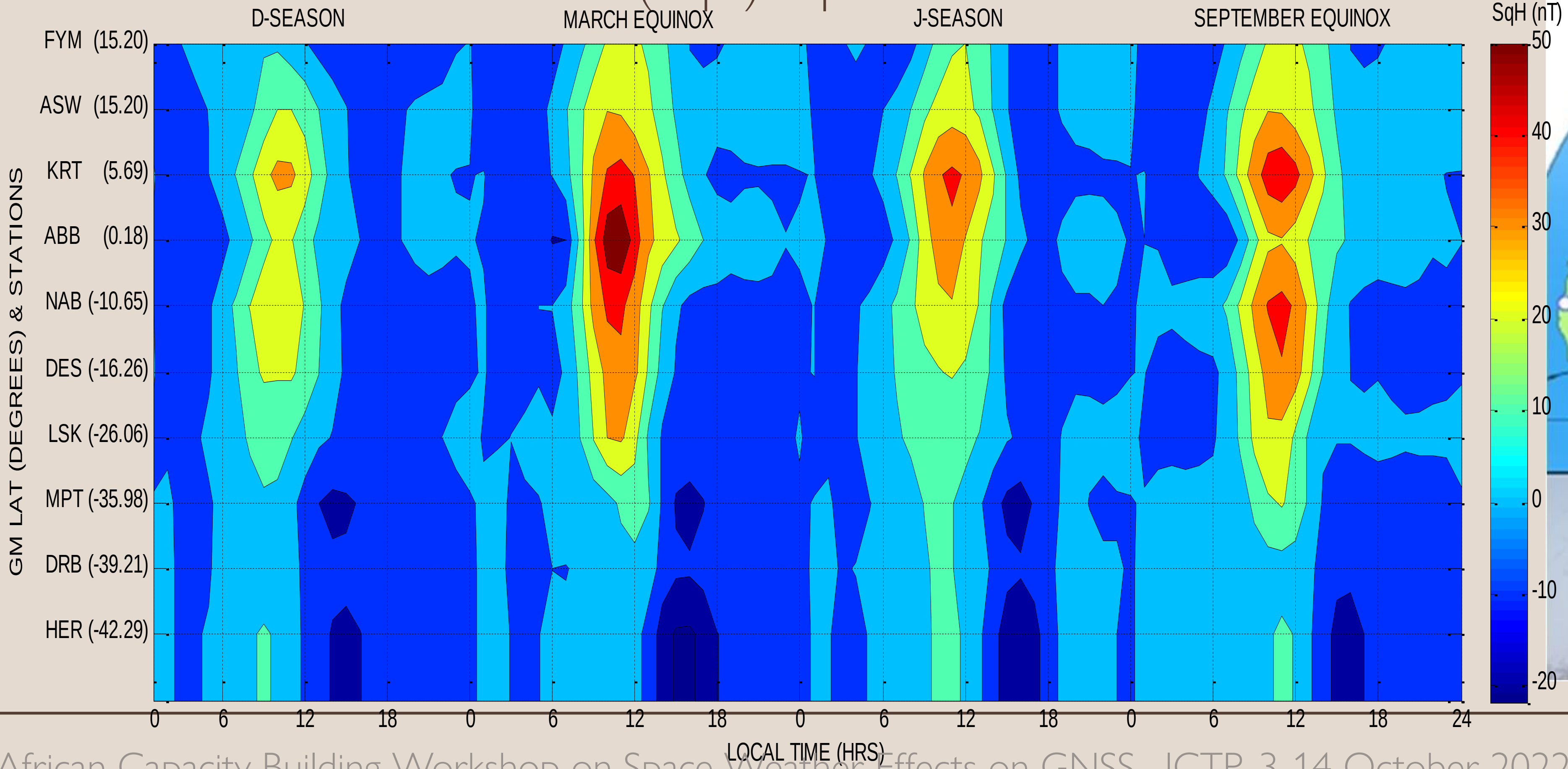
	Jo	Jm	Jm/Jo	Ifwd	Dip latitude of EEJ center
210 MM	112.13	-33.80	-0.299	32.67	-0.192
Indian Sector	62.97	-19.48	-0.312	19.01	-0.190
Brazil	148.00	-43.70	-0.290	67.00	-0.189

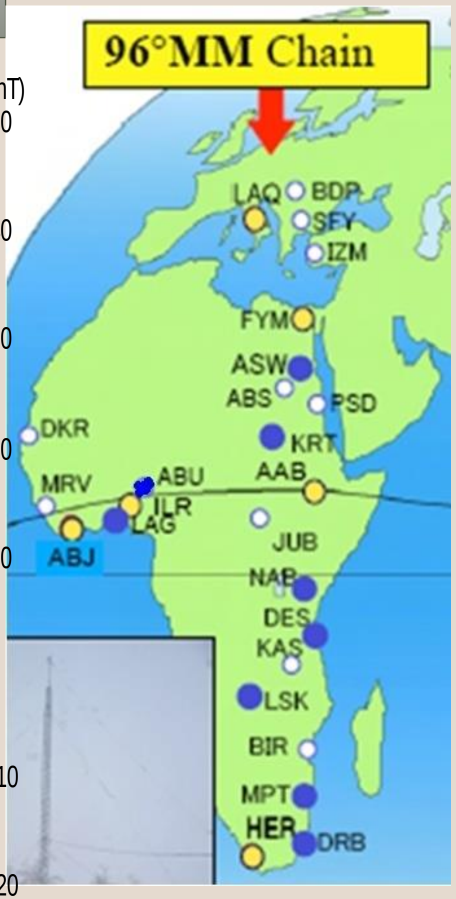
For 210° MM : Rabiu et al: (2009);
Brazil Sector: Rigoti et al, (1999);
Indian Sector: Rabiu et al (2013)

Seasonal variation of Sq(H) along the African low latitudes

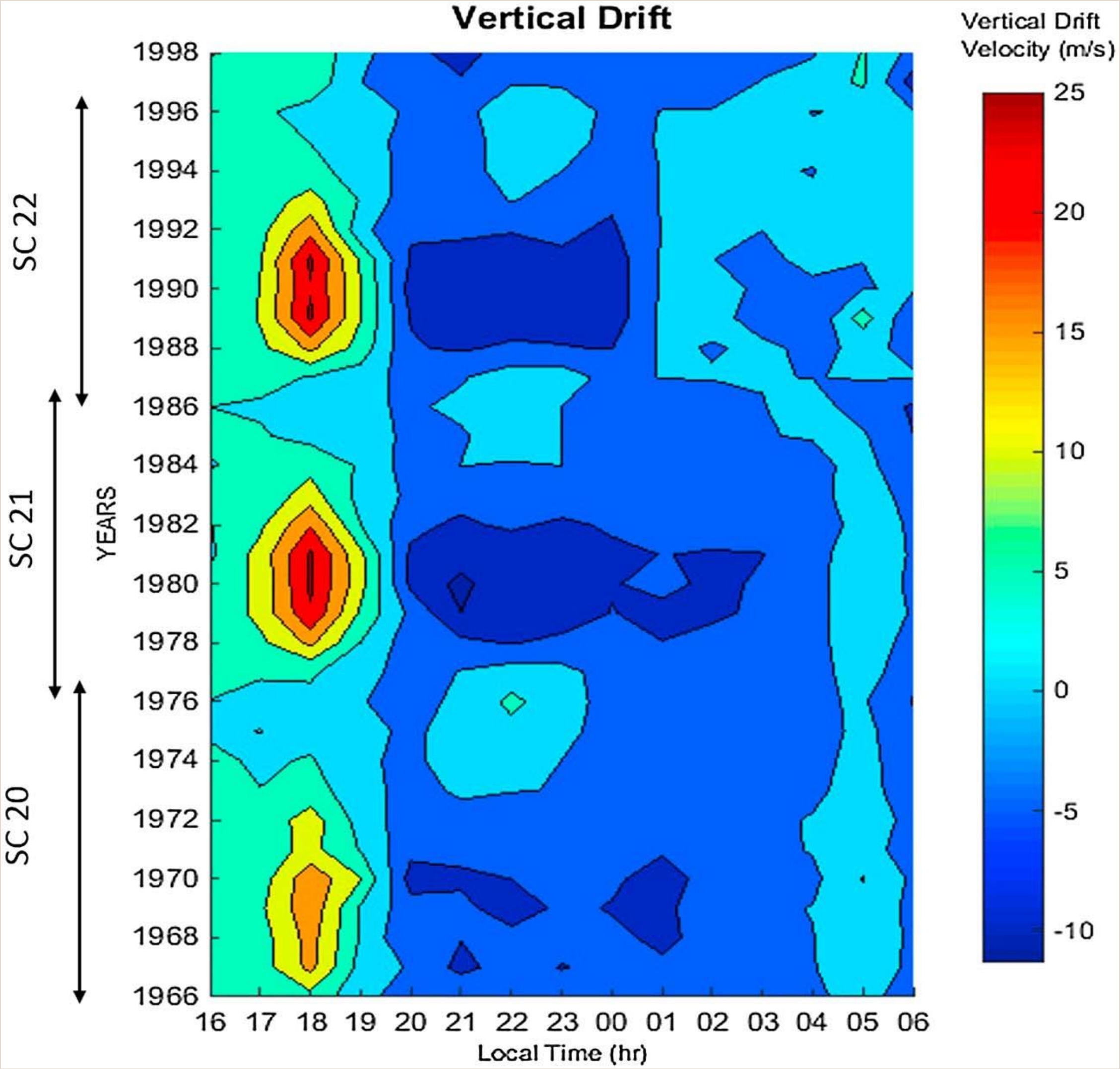
- Sq (H) is greater in all seasons in the neighbourhood of dip equator
- Obviously due to EEJ effect
- Max effect at Autumn (Sept) Equinox

Bolaji et al 2015 ..





Nighttime plasma drift over Ouagadougou using ionosonde data



Adebesin et al, 2015

- ✓ A remarkable feature is the consistent local presunrise drift enhancement for two SCs 20 and 21, which is not a regular feature of the equatorial ionosphere
- ✓ The rate of inhibition of scintillation effect increases with decreasing phase of sunspot activity and maximizes during the solstices.
- ✓ Both the PRE and minimum reversal peak magnitudes are influenced by the phase of sunspot cycle

Plasma bubbles over Nigeria using Optical imager

Percentage Occurrence of Plasma Bubbles as observed on the Airglow and GNSS data for the period from June 2015 to January 2017.

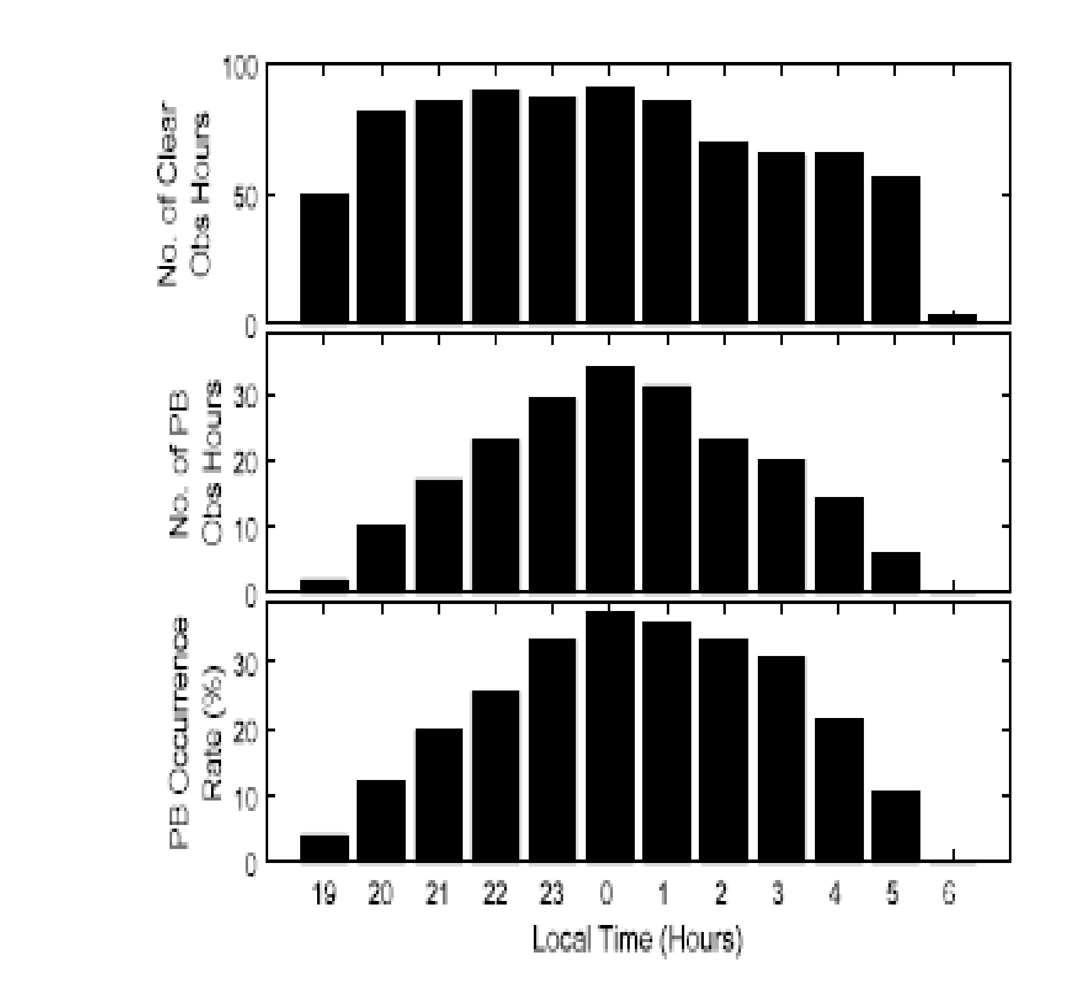
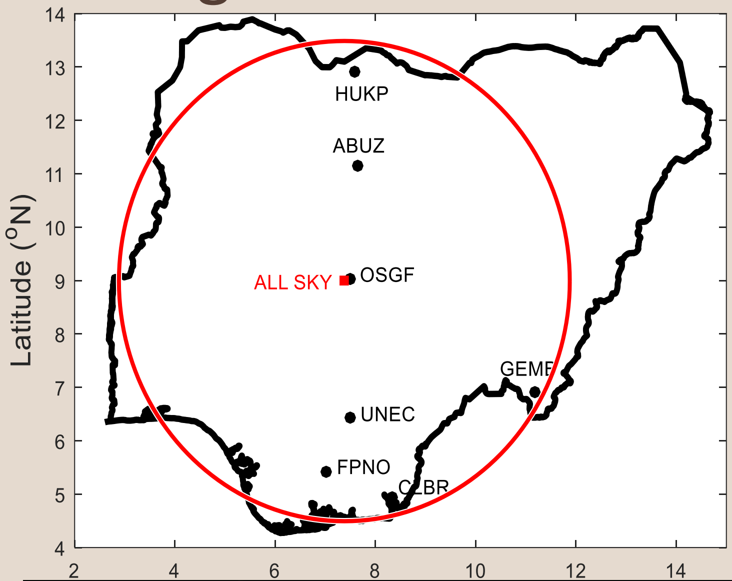
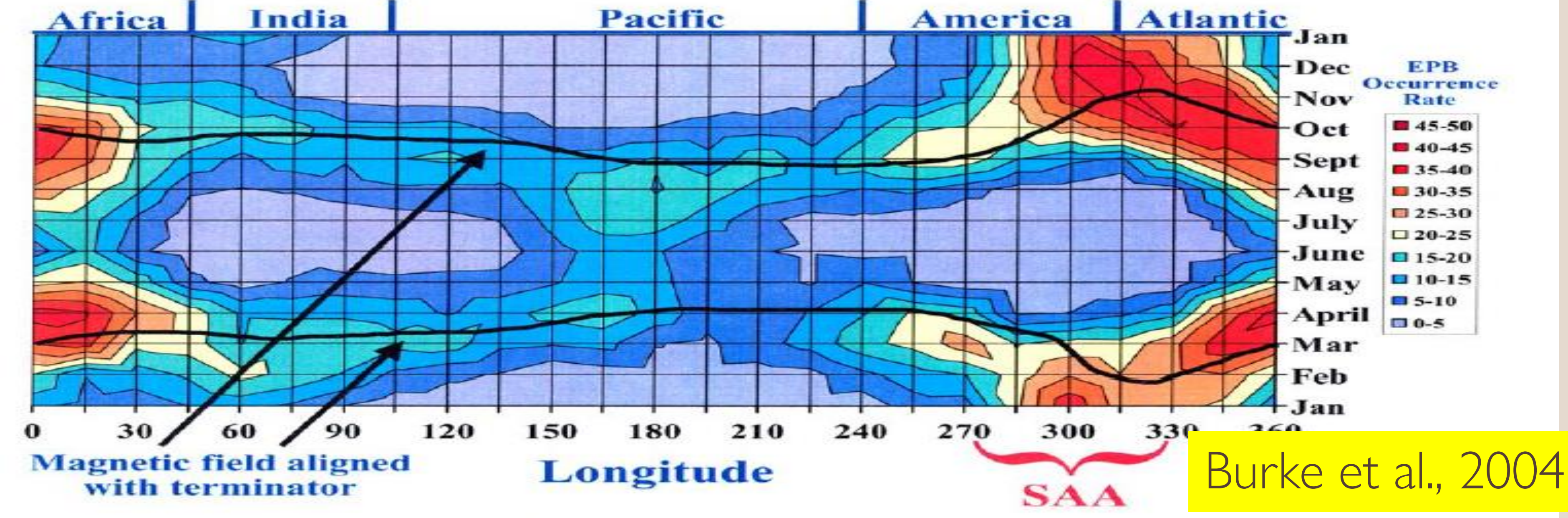


Figure 8. Percentage occurrence of plasma bubbles on the airglow images as a function of local time.

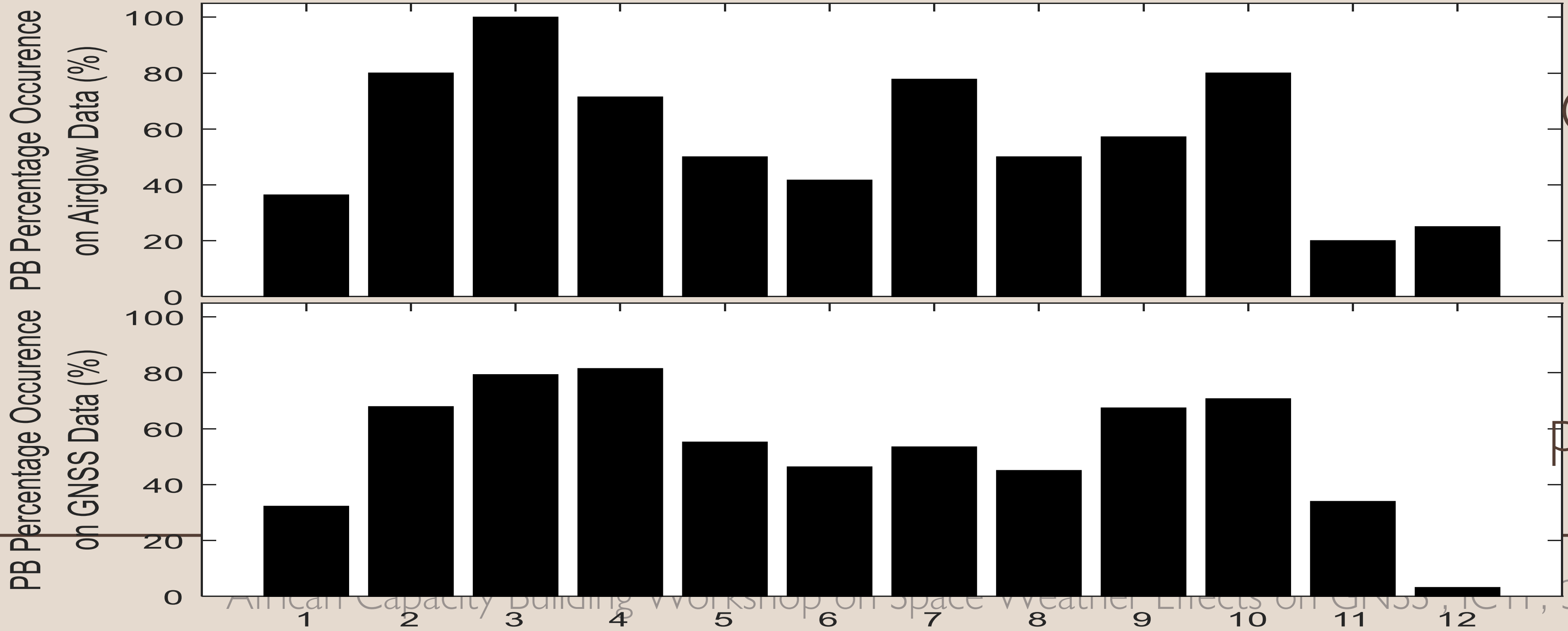


Okoh et al, 2017



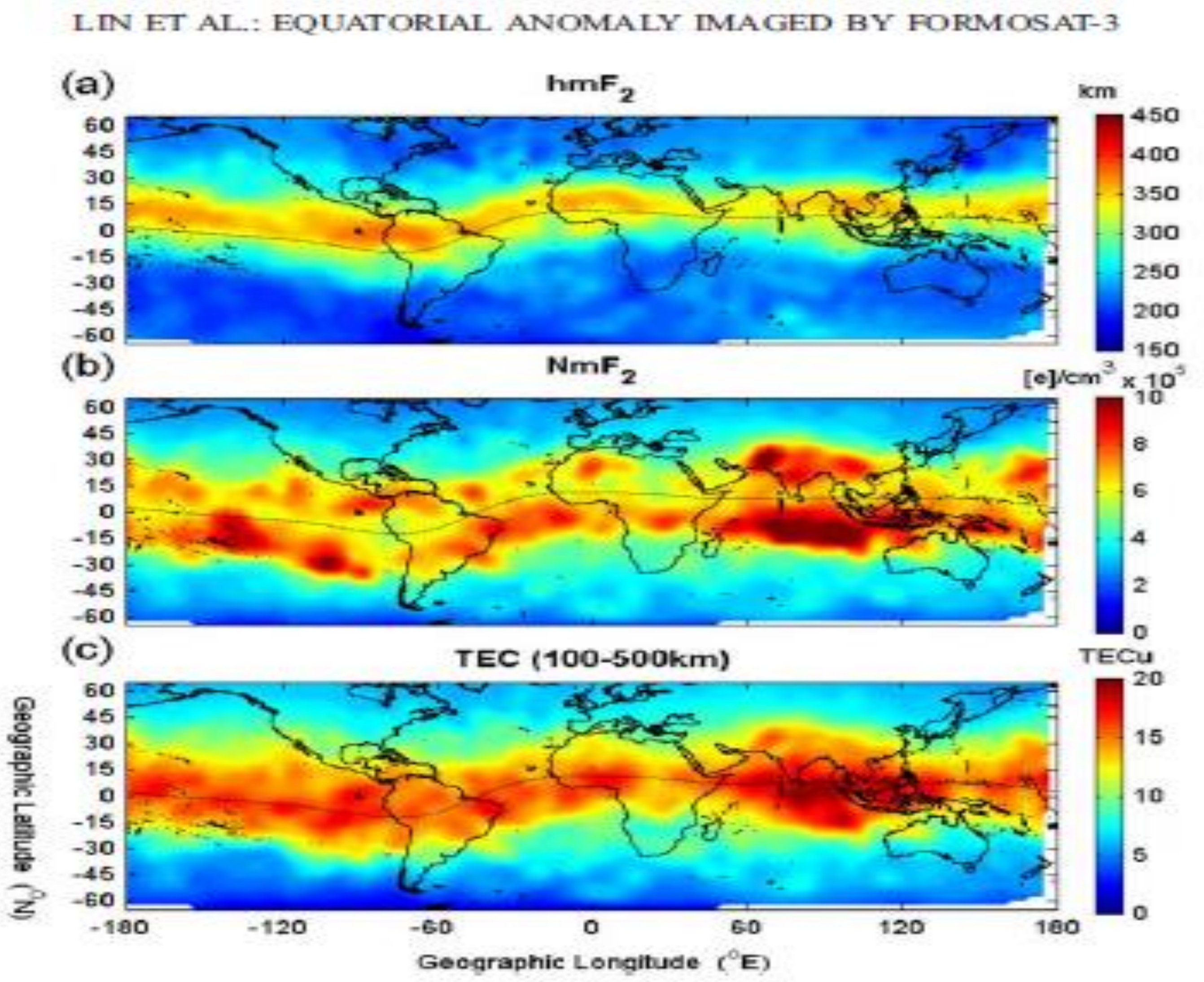
Burke et al., 2004

Figure 1. Contours of equatorial plasma bubble (EPB) occurrence rates measured by DMSP satellites between 1989 and 2002 plotted on a month versus longitude grid in nine 5% increments. The solid lines indicate the two times per year when $\alpha = 0°$ at given longitudes.



Percentage Occurrence of Plasma Bubbles as observed on the Airglow and GNSS data for the period from June 2015 to January 2017.

Okon et al, 2017



These longitudinal variations in EIA may be due to differences in:

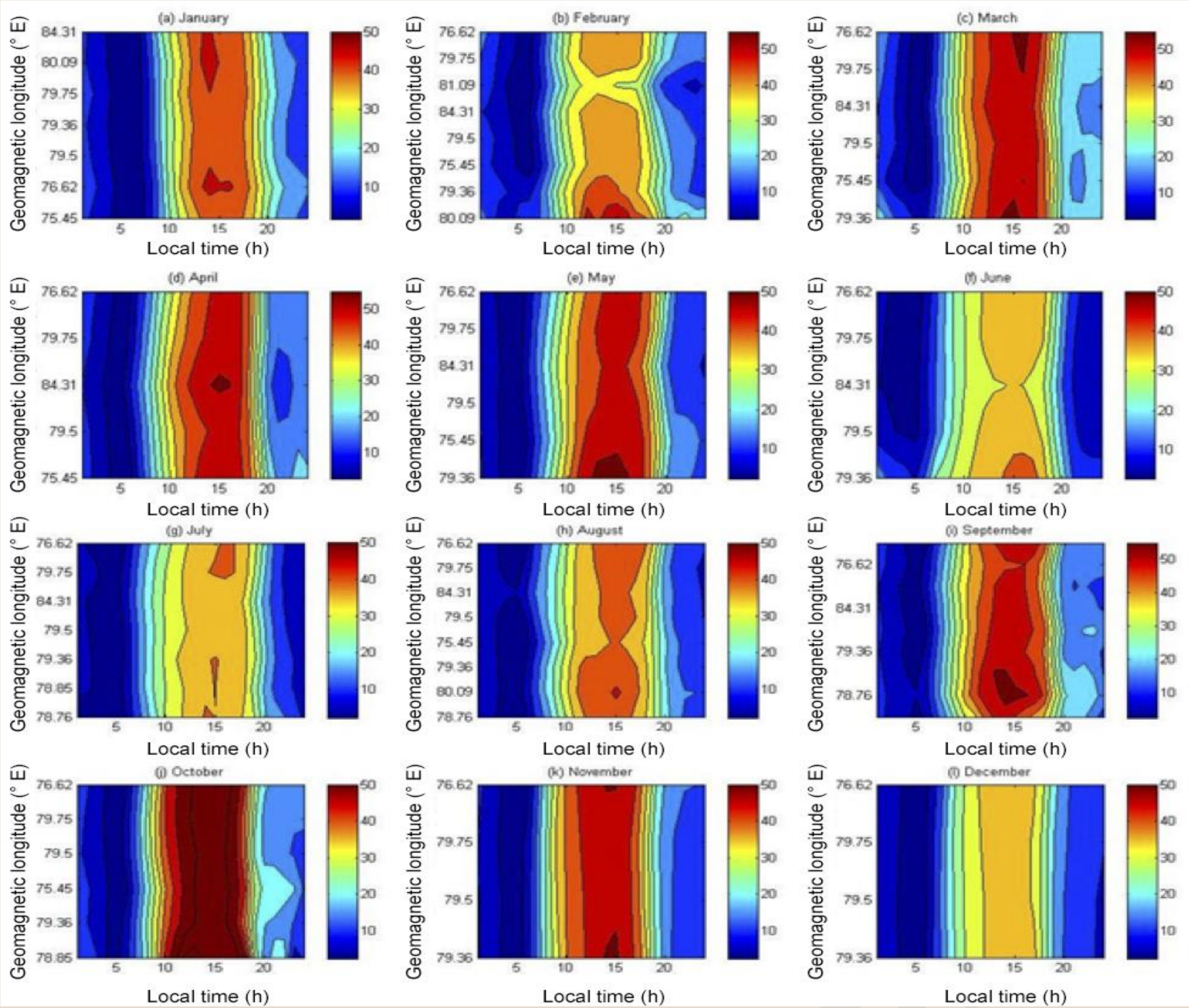
- ❑ magnetic declination
- ❑ E x B drift, and
- ❑ neutral winds in different longitudes.

Lin et al., 2007

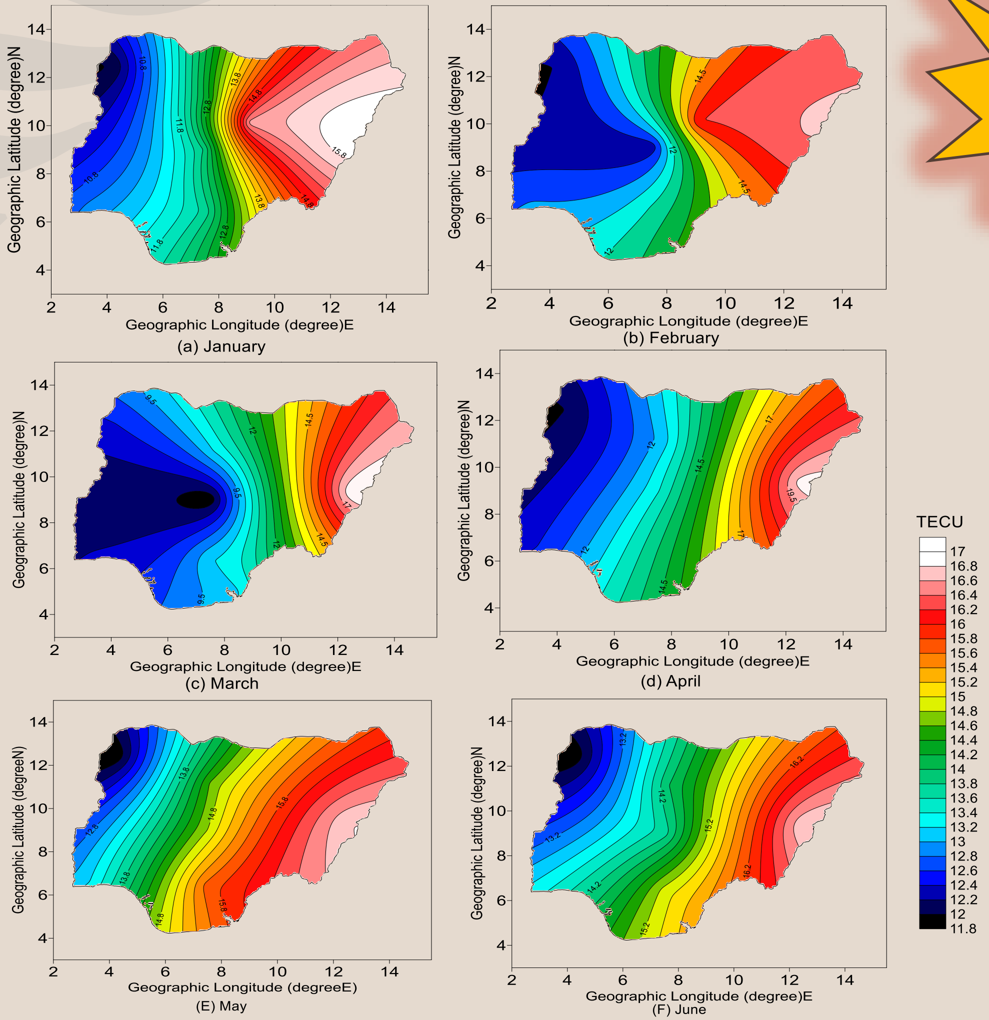
Ionospheric maps in (a) peak altitude (hmF2), (b) peak density (NmF2), and (c) total electron content (TEC) integrated between 100–500 km altitude range at global constant local time at 1200 LT.

Hourly variation in GPS TEC across Nigerian longitudes

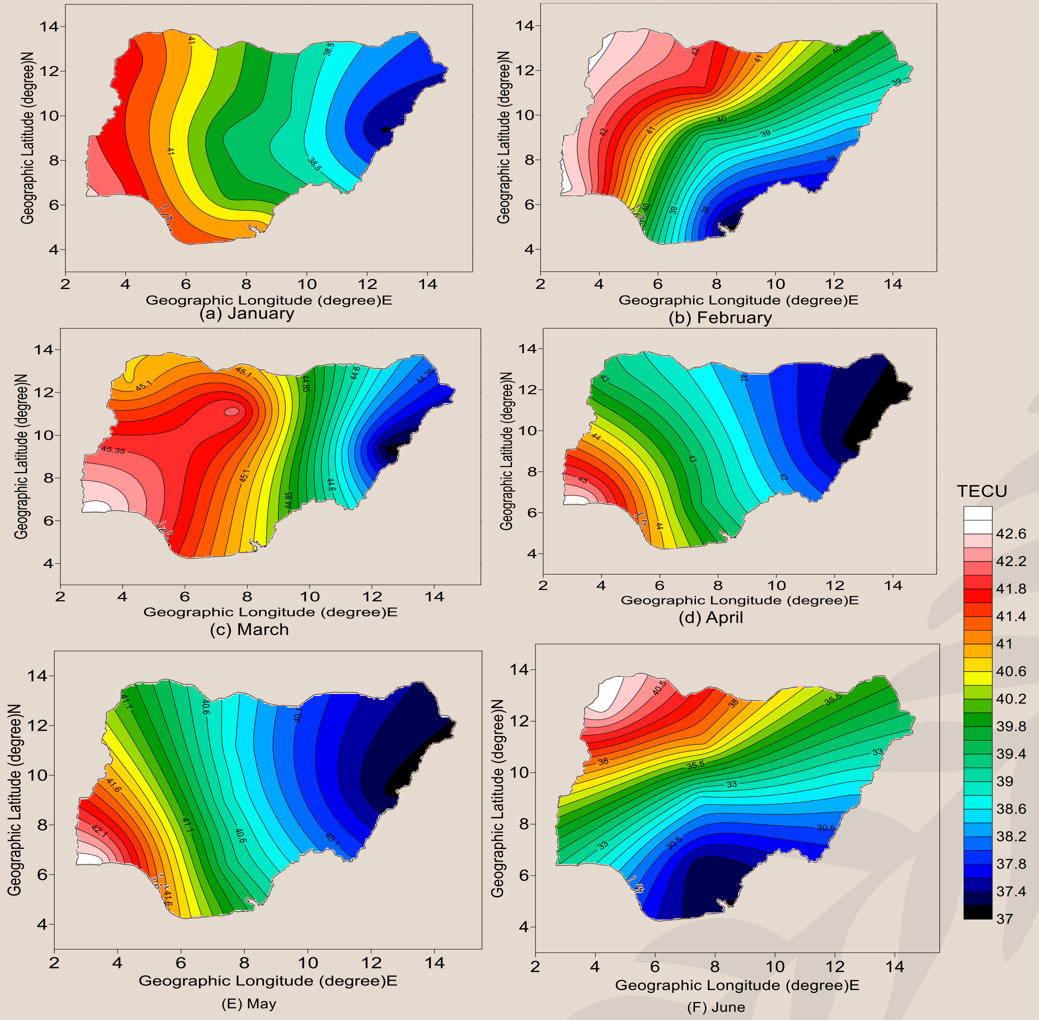
Eyelade et al., (2017)



Spatial variation of TEC in January to June



at 07:00LT (1 hr after Sunrise)



at 17:00LT (1 hr before Sunset)

Comparison of the Thermospheric Wind Speeds Obtained in Africa With Those of Other Regions From Existing Literatures

- Changes in these thermospheric neutral winds are the reason for the longitudinal differences that have been reported in equatorial electric fields between the West and East Africa stations (Bolaji et al., 2016; Rabiu et al., 2011, 2017; Yizengaw et al., 2014).
- The reality is that the geomagnetic main fields with respect to the dip equator over the West and East Africa are both almost horizontal.

Sector	Max zonal wind ms^{-1}	Max meridional wind ms^{-1}	References
West Africa	163	95	Rabiu et al 2021
East Africa	90	100	Tesema et al., 2017
Morocco, North Africa	100	75	Kaab et al., 2017
Morocco, North Africa	80	120	Malki et al., 2018
Peruvian	150	50	Martinis et al., 2001; Meriwether et al., 2011, 2017.
Brazilian	130	100	Makela et al., 2013; Meriwether et al., 2017

Rabiu et al 2021

Some facts

- The width of the EIA (northern crest to southern crest distance) is smaller in the American than in the Asian zone (Narasinga Rao, 1963) (longitudinal variability)
- The geometry of EIA (landmark properties) vary with local time, season, and solar cycle
- It has been shown that the EEJ controls the altitude of lifted plasma and the location of the crests of the equatorial ionization anomaly (Rama Rao et al., 2006a)
- Some literatures have also shown that the trough does not necessarily coincides with dip equator

Summary

- Equatorial ionosphere has dynamic longitudinal and transient variabilities
- New observational facilities have enabled new scientific results
- There is a great need for densification of ground observational facilities within the equatorial region to facilitate effective monitoring and modelling
- New approach and investigative tools are required in understanding the equatorial ionosphere
- New scientific results will surely improve our understanding of the region


THANK
YOU

Some References

- Narasinga Rao, B. C. (1963). Some characteristic features of the equatorial ionosphere and the location of the *F*-region equator, Journal of geophysical Research, 68. 2541-2549. https://doi.org/10.1029/JZ068i009p02541